ERDC/GSL TR-13-41

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Laboratory Performance Testing of Warm-Mix Asphalt Technologies for Airfield Pavements

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Final report

Prepared for US Air Force Civil Engineer Center
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Abstract

This report presents results from testing warm-mix asphalt (WMA) mixtures designed for airfield pavements. The study was conducted in two phases. The first phase included laboratory tests on 11 WMA technologies. The tests in Phase 2 were performed on three WMA mixtures and one hot-mix asphalt (HMA) mixture produced in an asphalt plant. The evaluation included performance tests to assess WMA susceptibility to permanent deformation and moisture damage compared to HMA produced using the same aggregate blend. Although WMA exhibited poorer performance than HMA in moisture damage tests on laboratory-produced specimens, the plant-produced mix indicated very little difference compared to HMA. Rutting potential for WMA was initially somewhat greater than for HMA for mixtures produced both in the laboratory and in an asphalt plant. Differences in performance among WMA mixtures were not attributed to a specific WMA technology category. Variations in performance test results between laboratory-produced specimens and plant-produced specimens were noted, indicating a need to require performance testing as part of a comprehensive quality assurance plan. Based on the laboratory performance test results of this study, WMA is a viable alternative to HMA for wearing surfaces on airfields.

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Preface

This study was conducted for the US Air Force Civil Engineering Center (AFCEC) under Project Number 320484. The technical monitor was George W. Vansteenburg.

The work was performed by the Airfields and Pavements Branch (GM-A) of the Engineering Systems and Materials Division (GM), US Army Engineer Research and Development Center, Geotechnical and Structures Lab (ERDC-GSL). At the time of publication, Dr. Gary L. Anderton was Chief, CEERD-GM-A; Dr. Larry N. Lynch was Chief, CEERD-GM; and Dr. David A. Horner, CEERD-GV-T, was the Technical Director for Force Projection and Maneuver Support. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Dr. David W. Pittman.

COL Jeffrey R. Eckstein was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
centipoises	0.001	pascal seconds
centistokes	1.0 E-06	square meters per second
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
foot-pounds force	1.355818	joules
gallons (US liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
inch-pounds (force)	0.1129848	newton meters
microns	1.0 E-06	meters
miles (US statute)	1,609.347	meters
miles per hour	0.44704	meters per second
mils	0.0254	millimeters
ounces (mass)	0.02834952	kilograms
pounds (force)	4.448222	newtons
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square yards	0.8361274	square meters
tons (2,000 pounds, mass)	907.1847	kilograms
yards	0.9144	meters

List of Symbols and Acronyms

a_1, a_2	fitting coefficients
α, β, δ, γ	fitting coefficients
a, b	regression constants
a, m	materials regression coefficients
AASHTO	American Association of Highway Transportation Officials
Abs	aggregate water absorption by mass of dry aggregate (%)
AFCEC	US Air Force Civil Engineering Center
APA	asphalt pavement analyzer
APB	Airfields and Pavements Branch
BBR	bending beam rheometer
CAA	coarse aggregate angularity (%)
CMB	Concrete and Materials Branch
δ	phase angle (degrees)
D'	viscoelastic compliance component at any time
D_o	instantaneous compliance
D/B	dust to effective binder ratio on mixture mass basis
DOT	department of transportation
DSR	dynamic shear rheometer
$D(t)$	total compliance at any time
$\|E^*\|$	dynamic modulus (psi)
ε_p	permanent strain
ERDC	US Army Engineer Research and Development Center
ESMD	Engineering Systems and Materials Division
ETL	Engineering Technical Letter
FAA	fine aggregate angularity (%)
F&E	aggregate flat and elongated particles (%)
G^*	binder complex shear modulus
G_b	binder specific gravity
G_{mb}	mixture bulk specific gravity
G_{mm}	mixture theoretical maximum specific gravity
G_{sa}	aggregate apparent specific gravity
G_{sb}	aggregate bulk specific gravity
G_{se}	aggregate effective specific gravity
GSL	Geotechnical and Structures Laboratory
HLWT	Hamburg loaded wheel tester
HMA	hot-mix asphalt

JMF	job-mix formula
LC-1	APA load case 1
LC-2	APA load case 2
LPLC	laboratory-produced and laboratory-compacted
m-value	slope of stiffness curve from BBR data
N	number of load cycles
N_{des}	number of design gyrations
NMAS	nominal maximum aggregate size
NT	not tested
$P_{12.5}$	passes to achieve 12.5-mm of rutting
PAV	pressure aging vessel
P_b	total binder content on mixture mass basis (%)
P_{ba}	absorbed binder content on aggregate mass basis (%)
P_{be}	effective binder content on mixture mass basis (%)
PG	performance grade
PPFC	plant-produced and field-compacted
PPLC	plant-produced and laboratory-compacted
QA	quality assurance
QC	quality control
RAP	reclaimed asphalt pavement
R_D	permanent rutting deformation without including uplift (mm)
RTFO	rolling thin film oven
SGC	Superpave gyratory compactor
SIP	stripping inflection point in HLWT
S_t	tensile strength
t	loading time
T	test temperature (°F)
T_R	reference tempeature (°F)
TSR	tensile strength ratio
UFGS	Unified Facilities Guide Specification
V_a	air voids (%)
VFA	voids filled with asphalt
VMA	voids in mineral aggregate (%)
WMA	warm-mix asphalt

1 Introduction

1.1 Background

The hot-mix asphalt (HMA) industry seeks emerging technologies that reduce environmental impact during production of bituminous paving materials. In recent years, warm-mix asphalt (WMA) has replaced HMA for many paving projects. In general, WMA is asphalt concrete produced at lower temperatures than conventional HMA (Anderson et al. 2008). Many techniques for producing WMA have been developed, including use of chemical additives, organic wax additives, and foaming agents. State departments of transportation (DOTs) are quickly beginning to adopt the use of WMA for roadway paving, and many are using it in place of conventional HMA (Hansen and Newcomb 2011). As state DOTs gain experience with WMA, conventional HMA may become less available for paving. Empirical evidence to date indicates that WMA performs well and can be adopted for use for airfield pavements. The US Army Corps of Engineers developed a Unified Facilities Guide Specification (UFGS) and an Engineering Technical Letter (ETL) providing guidance on the use of WMA on airfields based only on laboratory performance test data.

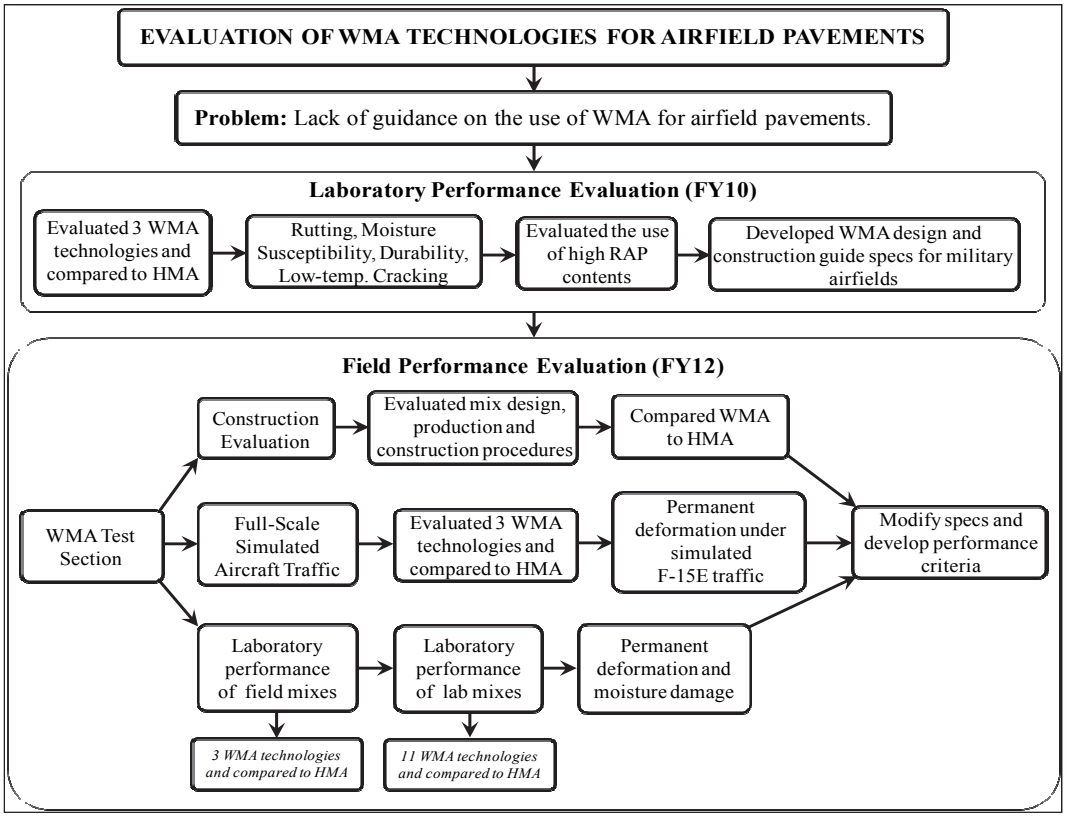
1.2 Previous work

The study presented in this report is part of a larger research effort that has been conducted by APB researchers to evaluate WMA technologies and provide guidance on their use for airfield pavements. A general description of the WMA research to date is summarized in the following paragraphs and presented in the flow chart in Figure 1.

In federal fiscal year 2010 (FY10), APB researchers were tasked by AFCEC to evaluate the laboratory performance of different WMA technologies for the purpose of certifying their use for airfield pavements. The performance of mixtures produced in the lab using different WMA technologies was compared to the performance of the same mixtures produced at HMA temperatures. Properties assessed included susceptibility to permanent deformation, moisture damage and low-temperature cracking, durability, and workability. The use of high reclaimed asphalt pavement (RAP) contents was also evaluated. Results indicated that WMA is a viable product for airfield pavement surface mixtures, and a Unified Facilities

Guide Specification (UFGS 32 12 15.16) and an Engineering Technical Letter (ETL 11-3) providing guidance on the use of WMA on airfields were developed. Specific details on the WMA laboratory evaluation conducted in FY10 are presented in Mejías-Santiago et al. (2012).

Figure 1. WMA research flow chart.



Currently, APB researchers are conducting additional research to validate the results of the laboratory performance evaluation using results from full-scale testing and from laboratory testing of plant-produced mixtures. This additional work focuses on three main areas of interest: 1) laboratory performance evaluation of field mixtures, 2) evaluation of production and construction procedures, and 3) evaluation of performance of full-scale test sections under simulated aircraft traffic. This report focuses on laboratory testing to compare performance of WMA to HMA.

1.3 Objective

The objective of this report is to present results from the laboratory portion of this WMA research and to document the performance evaluation of WMA relative to HMA in the context of military airfield applications.

2 Experimental Program

2.1 Research approach

This study included evaluation of the three main categories of WMA technologies: chemical additives, organic wax, and foaming agents or processes. A single aggregate blend representative of airfield specifications for gradation was designed and used throughout this study. Permanent deformation at high service temperatures (rutting) and moisture damage were the primary mixture performance categories considered. Based on findings of previous work (Mejías-Santiago et al. 2012), durability and cracking resistance of WMA were expected to be similar to or better than HMA and, thus, were assessed in this work through binder testing only.

The laboratory testing program for this project was conducted in two phases. Eleven WMA technologies and an HMA control were investigated in the laboratory during Phase 1 of the study and compared on a relative basis. HMA was prepared at conventional temperatures, and the temperature was approximately 30°C lower for the WMA mixtures. In the second phase, three warm-mix technologies selected from Phase 1 and an HMA control mixture were produced at full scale in an asphalt plant. Performance of the plant-produced material was then assessed in the laboratory. The mixtures produced in Phase 2 were placed and compacted with typical equipment. The field-compacted mixtures were then cored; the cores were tested; and the results were compared to those from laboratory-compacted specimens. Finally, performance of the plant-produced materials from Phase 2 was compared to that of the laboratory-produced materials from Phase 1.

2.2 Materials tested

2.2.1 Aggregates

Representative samples of each aggregate were obtained from producer stockpiles. Washed gradations, bulk specific gravities (G_{sb}), apparent specific gravities (G_{sa}) and water absorptions (*Abs*) were then determined in duplicate for each aggregate stockpile. The average of both determinations is provided in Table 1 for each aggregate. An aggregate blend was determined to meet Job-Mix Formula (JMF) gradation requirements for a 12.5 mm nominal maximum aggregate size (NMAS) mix according to UFGS 32-12-15 (2010). The blend consisted of 45% crushed gravel, 40%

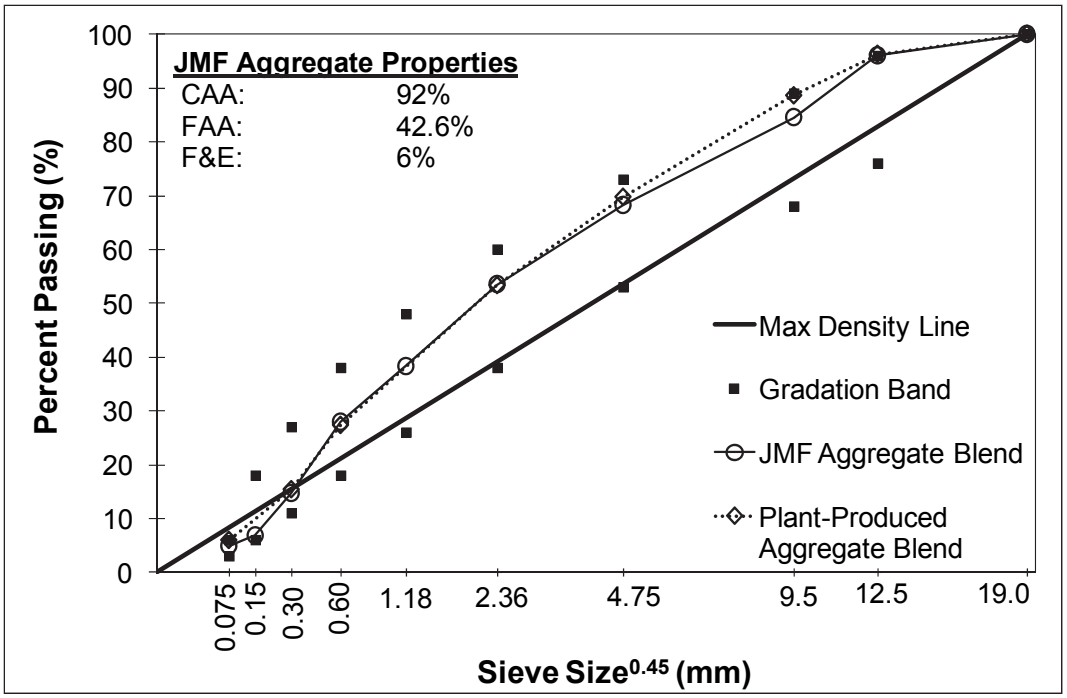
limestone, and 15% natural sand (maximum allowed by specification). The aggregate sources and blend were selected based on materials available for plant production in Phase 2. The JMF gradation was used for mixture design development and laboratory specimen production during Phase 1.

Table 1. Individual and combined aggregate gradations.

Aggregate	Limestone	Limestone	Limestone	Gravel	Sand	JMF Blend
Size	#7	#11	<4.75 mm	<19.0 mm	<9.5 mm	12.5 mm NMAS
Percent Used	15	20	25	25	15	100
- 25.0 mm	100	100	100	100	100	100
- 19.0 mm	100	100	100	100	100	100
- 12.5 mm	90.3	100	100	89.9	100	96.0
- 9.5 mm	46.1	100	100	70.5	100	84.5
- 4.75 mm	3.7	97.3	100	34.4	97.3	68.2
- 2.36 mm	1.6	61.7	91.3	18.2	90.4	53.5
- 1.18 mm	1.5	35.6	61.5	10.8	85.6	38.3
- 0.60 mm	1.5	24.2	39.2	6.9	75.7	27.9
- 0.30 mm	1.4	17.0	21.4	4.4	30.8	14.7
- 0.15 mm	1.3	13.1	10.0	3.0	4.9	6.8
- 0.075 mm	1.2	10.8	6.4	2.1	2.7	4.9
G_{sb}	2.675	2.586	2.684	2.524	2.600	2.609
G_{sa}	2.725	2.677	2.764	2.625	2.653	2.688
Abs (%)	0.69	1.33	1.08	1.56	0.78	1.15

Requirements for coarse-aggregate angularity (CAA) and flat and elongated particles (F&E) at a 3:1 ratio were met. However, the fine-aggregate angularity (FAA) value for this blend was 42.6%, which is below the specified minimum requirement of 45.0% and could indicate an increased propensity for rutting. Gradation and aggregate properties for the JMF aggregate blend, as well as the gradation from solvent-extracted material produced in the plant during Phase 2, are provided in Tables A1 and A2 of the appendix, and Figure 2 presents a plot of average aggregate gradation. The plant-produced aggregate blend was generally close to the JMF target blend. As is common with plant-produced mix, the percentage passing the #200 (0.075-mm) sieve was higher than that of the JMF target. For the #200 sieve, deviations from the JMF ranged from +0.6 to +1.1%, which is within the specification limits of up to 1.4% action limit and 2% suspension limit. Deviations from the JMF were likely caused by variations in stockpile gradations and aggregate breakdown during production.

Figure 2. Properties of job mix formula (JMF) aggregate blend.



2.2.2 Asphalt binder

The base asphalt binder for this project was an unmodified performance grade (PG) 67-22 produced by Ergon Asphalt and Emulsions, Inc., at their Vicksburg, Mississippi, facility. An unmodified binder was specifically selected for this project to avoid the possibility of secondary interactions between asphalt modifiers and the WMA technologies. Results of asphalt binder testing for the base binder and WMA technologies are presented in the Chapters 3 and 4 for Phase 1 and Phase 2, respectively. Laboratory mixing and compaction temperatures for the HMA were based on data provided by the supplier and were 160°C (320°F) and 146°C (295°F), respectively. For the WMA, both mixing and compaction temperatures were dropped by 30°C (55°F).

2.2.3 Warm-mix additives

Eleven warm-mix technologies were evaluated in Phase 1 and compared to the HMA control. Table 2 explains the nomenclature used in this study to identify each binder and provides details of the warm-mix technologies evaluated and their respective dosage rates. Warm-mix dosage rates were selected based on manufacturer's recommendations. When a range of dosage rates was recommended, the median dosage rate was selected. In Phase 1, all the warm-mix additives were pre-blended with the base binder

prior to use with the exception of the foam process (Binder 4) and the foaming additive (Binder 12), which are described in the specimen preparation section of this chapter. Each additive was mixed into the base binder with a high shear mixer for 10 min. All 12 mixtures were evaluated in Phase 1. For Phase 2, one warm-mix technology from each major category was selected for full-scale production (Mixtures 1 to 4) based on local availability of WMA products for full-scale production. Details of incorporation of WMA products during production are discussed in Rushing et al. (2013).

Table 2. Nomenclature and dosage rates for warm mix additives.

Mixture ID	Product Name	Manufacturer	WMA Category	Dosage Rate[a] (%)
1	PG 67-22	Ergon	---	---
2	Sasobit®	SasolWax	organic wax	1.5
3	Evotherm™ 3G	MeadWestvaco	chemical additive	0.5
4	Foam (water)	---	foam process	2.0
5	SonneWarmMix™	Sonneborn	organic wax	0.6
6	Asphaltan B	Romonta	organic wax	2.5
7	QualiTherm™	QPR®	chemical additive	0.2
8	Rediset WMX-8017A	AkzoNobel	chemical additive	1.5
9	Cecabase RT Bio 10	Ceca Arkema Group	chemical additive	0.4
10	Licomont BS 100	Clariant	chemical additive	3.0
11	Bitutech PER	Engineered Additives	chemical additive	0.6
12	Advera®	PQ Corporation	foam additive	0.25[b]

a) Dosage rate by percentage of binder weight unless otherwise specified.

b) Dosage rate by percentage of mixture weight.

2.2.4 Asphalt mixtures

Volumetric properties of all Phase 1 laboratory-produced mixtures are provided in Table 3; raw data are located in Tables A3 and A4 of the appendix. Asphalt Mixtures 1 to 4 were designed to 75 gyrations (N_{des}) in the Superpave Gyratory Compactor (SGC) according to UFGS 32-12-15 specification requirements. The design total binder content (P_b) was selected as the binder content that resulted in a compacted specimen having 4% air voids (V_a). To provide a consistent set of volumetric properties for comparison throughout Phase 1 of this study, all remaining mixtures were produced with effective asphalt contents (P_{be}) of 4.45±0.05%. For a given aggregate blend and binder grade, changes in P_{be} will affect rutting

performance. Mixture 4a was substituted for Mixture 4 in the Phase 1 laboratory test matrix to provide volumetric properties within the desired P_{be} range. For the foamed asphalt mixtures 4, 4a, and 12, the water added to the binder was removed for volumetric calculations, since this water evaporates relatively quickly and does not remain as part of the binder. All mixtures generally meet the volumetric requirements, though air voids and voids in mineral aggregate (VMA) values are slightly, but not significantly, lower than the targets in a few cases.

Table 3. Volumetric properties of laboratory-produced mixtures in Phase 1.

Mix ID	G_{mm}	G_{se}[a]	G_{mb}	P_b	P_{ba}[a]	P_{be}	V_a	VMA	VFA	D/B
1	2.461	2.668	2.362	5.3	0.87	4.48	4.0	14.3	72.0	1.04
2	2.463	2.666	2.367	5.2	0.84	4.40	3.9	14.0	72.2	1.06
3	2.463	2.666	2.368	5.2	0.84	4.40	3.9	14.0	72.1	1.06
4	2.467	2.666[b]	2.369	5.1[c]	0.85[b]	4.29[b]	4.0	13.8[b]	71.1[b]	1.08[b]
4a	2.459	2.661[b]	2.375	5.2[c]	0.78[b]	4.46[b]	3.4	13.7[b]	75.2[b]	1.04[b]
5	2.458	2.660	2.361	5.2	0.76	4.48	4.0	14.2	71.9	1.04
6	2.460	2.662	2.361	5.2	0.79	4.45	4.0	14.2	71.8	1.04
7	2.458	2.655	2.365	5.1	0.69	4.45	3.8	14.0	72.9	1.05
8	2.459	2.662	2.365	5.2	0.78	4.46	3.8	14.1	73.0	1.04
9	2.459	2.662	2.369	5.2	0.78	4.46	3.7	13.9	73.4	1.04
10	2.460	2.663	2.372	5.2	0.80	4.44	3.6	13.8	73.9	1.05
11	2.460	2.658	2.365	5.1	0.72	4.41	3.9	14.0	72.1	1.05
12	2.457	2.655[b]	2.367	5.1[c]	0.69[b]	4.47[b]	3.7	13.9[b]	73.4[b]	1.04[b]
Target	---	---	---	---	---	---	4	min 14.0	65-78	0.8-1.2

a) An asphalt binder specific gravity (G_b = 1.03) was assumed and used for all volumetric calculations.

b) Calculated using the adjusted total asphalt content.

c) Total asphalt content was adjusted to account for the water added to the binder. Nominal asphalt contents with water included were 5.2, 5.3 and 5.2 for mixtures 4, 4a and 12, respectively.

Overall, the 30°C drop in mixing and compaction temperatures from HMA to WMA caused a 0.1 to 0.2 percentage point reduction in the total asphalt contents, while the effective asphalt contents remained similar. This indicates that a considerable portion of the reduction in design asphalt content was likely due to reduced absorption of binder by the aggregate. The absorbed asphalt contents (P_{ba}) for WMA mixtures are lower than for the HMA, which supports this position. Previous research has also indicated reduced asphalt absorption for WMA compared to HMA for aggregates with intermediate to high water absorption (Doyle et al., 2011). This effect is potentially beneficial, since it reduces material costs. For example, the

0.2 percentage point reduction in P_b for the WMA mixtures in this study will result in a raw material cost reduction on the order of 1 to 2%.

During Phase 2, Mixtures 1 through 4 were produced at full scale in an asphalt plant. The asphalt contractor performed quality control (QC) testing of the mixtures during production, while the research team performed quality assurance (QA) testing during production. Results are summarized in Table 4, and the raw data may be found in Table A5 of the appendix. In general, V_a and voids in mineral aggregate (VMA) values from QC and QA data were a bit lower than the target and voids filled with asphalt (VFA) and dust to effective binder ratio (D/B) values were a bit higher. This is indicative of a mixture where the voids have been closed by an excess of binder or aggregate dust. Since P_b values are generally at or below the JMF target and P_{be} values are not excessively high, the increased dust content of the gradation during plant production discussed earlier was likely the primary cause of the mixture void closure. The variation of asphalt absorption during production and construction is examined in chapter 4 of this report and also discussed in Rushing et al. (2013).

Table 4. Volumetric properties of all plant-produced mixtures in Phase 2.

Mix ID	G_{mm}	G_{se}	G_{mb}	P_b	P_{ba}	P_{be}	V_a	VMA	VFA	D/B
1-QC[a]	2.444	2.645	2.388	5.3	0.54	4.75	2.3	13.3	83	1.20
2-QC[a]	2.442	2.643	2.389	5.3	0.51	4.77	2.2	13.3	84	1.09
3-QC[a]	2.456	2.650	2.413	5.0	0.61	4.46	1.7	12.2	86	1.29
4-QC[a]	2.448	2.638	2.402	5.0	0.43	4.55	1.9	12.5	85	1.24
1-QA[b]	2.454	2.659	2.399	5.3	0.74	4.58	2.3	12.9	82	1.16
2-QA[b]	2.460	2.650	2.384	4.9	0.61	4.33	3.1	13.1	76	1.21
3-QA[b]	2.463	2.652	2.414	4.9	0.64	4.27	2.0	12.0	83	1.61
4-QA[b]	2.471	2.660	2.356	4.8	0.76	4.11	4.7	14.1	67	1.50
Target	---	---	---	---	---	---	3-5	min 14.0	65-78	0.8-1.2

a) Average results from producer's Quality Control (QC) testing.

b) Average results from researcher's Quality Assurance (QA) testing.

2.3 Specimen preparation

The following nomenclature is used to describe the production and compaction of specimens for this study:

- LPLC Laboratory-produced and laboratory-compacted
- PPLC Plant-produced and laboratory-compacted
- PPFC Plant-produced and field-compacted

2.3.1 Phase 1: Laboratory asphalt production

For laboratory production and compaction of asphalt mixtures during Phase 1, the material handling, mixing and compaction process was as follows: Individual aggregate materials were first oven-dried overnight to remove all moisture. Aggregates were then screened into several size fractions to permit better control of gradation. The #7 limestone aggregate was screened into three size fractions (-19.0 mm to +9.5 mm, -9.5 mm to +2.36 mm, and -2.36 mm to pan). The <19.0 mm crushed gravel aggregate was screened into four size fractions (-19.0 mm to +9.5 mm, -9.5 mm to +4.75 mm, -4.75 mm to +2.36 mm, and -2.36 mm to pan). The #11 limestone aggregate, the <4.75 mm limestone aggregate, and the <9.5 mm natural sand aggregate were not screened into separate size fractions. The different size fractions of each aggregate and the un-fractionated aggregates were each separately mixed and carefully handled to minimize segregation.

Aggregate samples were batched to meet the target aggregate blend and then heated for a minimum of 4 hr to overnight to approximately 2°C (4°F) greater than the desired mixing temperatures, which were 160°C (320°F) for the HMA and 129°C (265°F) for the WMA mixes. Binder was heated to 154°C (310°F) for all HMA and WMA with the exception of the foam process WMA mixture (Binder 4). For Binder 4, the laboratory asphalt foaming device described in Mejías-Santiago et al. (2012) was used to produce foamed asphalt from the base binder; the binder temperature was set to 160°C (320°F), and the binder discharge temperature was set to 149°C (300°F). For the foam additive WMA mixture (Binder 12), the correct dosage of additive was weighed out for each material batch and added just before mixing.

Aggregate and binder were combined ed for 60-90 sec in a laboratory asphalt bucket mixer until thoroughly coated. No problems were observed with coating aggregates for the WMA mixtures. After mixing, the loose-asphalt mixture was short-term oven conditioned at the compaction temperature for 2 hr before compaction. Laboratory compaction temperatures were 146°C (295°F) for the HMA and 116°C (240°F) for the WMA mixtures.

All compaction was performed with a SGC. The SGC used was a Pine Instruments Company model AFGC125X with a ram pressure of 600 kPa (87 psi) and an internal angle of gyration of 1.16°±0.02°. Two modes of compaction were used: (1) compaction to the design gyration (N_{des}) level of

75 gyrations; and (2) compaction to a target specimen height and density for performance test specimens.

2.3.2 Phase 2: Full-scale asphalt production

For Phase 2, the material handling and mixing process for plant production of asphalt mixtures is described in Rushing et al. (2013). Material was sampled from haul trucks at the laydown site, taken to the laboratory while still hot, and used for QA testing and compaction of some of the performance test specimens. Additional sampled material was allowed to cool to room temperature and then later reheated to the compaction temperature to produce additional performance test specimens using the same compaction process described in the previous section. Reheating of some specimens was necessary, because the number of required specimens could not be compacted during a reasonable timeframe.

2.4 Test methods

2.4.1 Aggregate, asphalt binder and mixture

Washed aggregate gradations were determined in accordance with the American Association of Highway Transportation Officials (AASHTO) standard test procedures T 11 and T 27 during mix design and in accordance with AASHTO T 30 for extracted aggregate during Phase 2. Specific gravity and absorption of aggregates were determined in accordance with AASHTO T 84 and T 85. Other aggregate properties were determined in accordance with COE CRD-C171 for coarse-aggregate angularity (CAA), ASTM D4791 for flat and elongated (F&E) particles, and ASTM C1252 for fine-aggregate angularity (FAA).

In Phase 1, properties of the base binder and all WMA binders with organic or chemical additives were tested in accordance with AASHTO T 316, T 315, T 240, T 313, and standard recommended practice R 20. The data were used to determine the continuous performance grade (PG) in accordance with AASHTO standard specification M 320. Asphalt content of the plant-produced mixture in Phase 2 was determined by the nuclear method (AASHTO T 287) for QC data. For QA data, asphalt content was determined by AASHTO T 164 Method A using trichloroethylene as the extraction solvent. Binder from the solvent extraction was then recovered by rotary evaporation in accordance with AASHTO T 319. Recovered binder was then tested and graded as described above except that the

rolling thin film oven (RTFO) test (AASHTO T 240) was not conducted and the binder was graded based on post-production properties only.

Theoretical maximum specific gravity (G_{mm}) of each mixture was determined on duplicate specimens in accordance with AASHTO T 209, and the average value was reported. Bulk specific gravity (G_{mb}) of compacted cylindrical specimens was determined in accordance with AASHTO T 166 and AASHTO T 331. Mixture volumetric properties were determined in accordance with procedures in the Asphalt Institute MS-02 manual (1997).

2.4.2 Tensile strength ratio

To assess the moisture damage resistance of the mixtures, testing for tensile strength ratio (TSR) was performed in accordance with ASTM D4867. In Phase 1, after short-term oven conditioning, 100-mm-diameter by 62.5-mm-thick specimens were compacted in the SGC to an air void content of 7±1.0 %. In Phase 2, re-heated mixture was compacted in the same fashion. A freeze-thaw cycle was not included as part of the moisture conditioning process.

2.4.3 Hamburg Loaded Wheel Tracker (HLWT)

To assess the combined moisture damage resistance and rutting performance of the mixtures, Hamburg loaded wheel tracker (HLWT) testing was performed in accordance with AASHTO T 324. In Phase 1, after short-term oven conditioning, 150-mm-diameter by 63-mm-thick specimens were compacted in the SGC to an air void content of 7±0.5% measured in accordance with AASHTO T 331. In Phase 2, hot or re-heated mixture was compacted in the same fashion. Also in Phase 2, 150-mm-diameter cores were taken of the field-compacted mixture, trimmed to the correct thickness and tested. The test temperature was 50°C (122°F) as is typical for the test.

2.4.4 Asphalt Pavement Analyzer (APA)

To assess rutting performance of the mixtures, Asphalt Pavement Analyzer (APA) wheel track testing was performed in accordance with AASHTO T 340, except as discussed below. The shear stresses produced by aircraft loads on the surface course of a pavement are much higher than those produced by ordinary truck traffic. Since the loading conditions typically used in the APA are intended to approximate the stress conditions

imposed by truck traffic, modifying the APA to better represent aircraft loading conditions was necessary. Two sets of modified APA loading conditions were used. The first was a tube or hose pressure of 1724 kPa (250 psi) and a wheel load of 1113 N (250 lb) as recommended by Rushing et al. (2012) for typical commercial aircraft conditions; hereafter this set of loading parameters is referred to as load case 1 (LC-1). The second set of conditions was a tube or hose pressure of 2241 kPa (325 psi) and a wheel load of 1446 N (325 lb) hereafter referred to as load case 2 (LC-2). LC-2 was intended to represent the stress conditions targeted in the full-scale simulated F-15E military fighter aircraft traffic tests described in Mejías-Santiago et al. (2013).

In Phase 1, two types of specimens were tested. The first was produced by trimming the 150-mm-diameter specimens compacted to N_{des} gyrations used to verify volumetric properties (i.e., target V_a = 4%) to a 75-mm thickness. These specimens were tested with LC-1 and the test temperature was 64°C (147°F) as ordinarily used for the base binder grade. The second type was 150-mm-diameter by 75-mm-thick specimens compacted in the SGC after short-term oven conditioning to 7±0.5% air void content measured in accordance with AASHTO T 331. These specimens were tested with LC-2, and the test temperature was 43°C (109°F). These test conditions were intended to represent the temperature and stress conditions targeted in the full-scale simulated aircraft trafficking described in Mejías-Santiago et al. (2013).

In Phase 2, hot or re-heated mixture was compacted into 150-mm-diameter and 75-mm-thick specimens with target air voids, measured in accordance with AASHTO T 331, of either 4±0.5%, 5±0.5% (matching average air voids of field-compacted mixture), or 7±1%, depending on the intended testing purpose. Also in Phase 2, 150-mm-diameter cores were taken of the field-compacted mixture, trimmed to the correct thickness, and tested. In addition to the two load and temperature test conditions described above, testing was also performed with LC-2 at temperatures of 37°C (99°F) and 49°C (120°F). These extra test temperatures were to account for the temp variation observed in the full-scale simulated aircraft traffic tests described in Mejías-Santiago et al. (2013).

For APA data, the rate of permanent rutting deformation (R_D) is defined as the permanent downward deformation beneath the center of the APA loading hose without including uplift. R_D can be mathematically expressed

using the power-law model in Equation 1. The regression coefficients for intercept (a) and slope (b) are determined from APA rut depth data. Equation 1 was fit to APA data from 500 cycles to the end of the test when possible; some tests reached the failure criterion and terminated prior to 500 cycles.

$$R_D = a \times N^b \quad (1)$$

where:

R_D = permanent rutting deformation without including uplift (mm)
N = number of load cycles
a, b = regression constants

2.4.5 Static load-creep

To assess permanent deformation characteristics of the mixtures, the static load-creep test was performed according to the general procedure described in Witczak et al. (2002). In Phase 1, after short-term oven conditioning, 150-mm-diameter by 170-mm-thick specimens were compacted in the SGC to a target air void content of 4±0.5% in accordance with AASHTO T 166. In Phase 2, re-heated mixture was compacted in the same fashion. The SGC-compacted specimens were then cored and sawn to produce test specimens 100 mm in diameter by 150 mm high. The confined test was selected to more closely represent field conditions, with a confining stress of 276 kPa (40 psi) and deviator stress of 1380 kPa (200 psi) recommended by Rushing (2013). The test temperature was 43°C (109°F) to match the target temperature in the full-scale traffic tests described in Mejías-Santiago et al. (2013).

From the static load-creep test data, 4 parameters are determined; they are summarized here with additional details of the data reduction process provided in Rushing (2013). The first two parameters are flow time (FT) and tertiary flow number (TF). In addition, the secondary phase of the creep compliance curve can be quantified using a power model in the form listed in Equation 2. The regression coefficients for intercept (a) and slope (m) are outputs of the static load-creep test.

$$D' = D(t) - D_o = a \times t^m \quad (2)$$

where:

D' = viscoelastic compliance component at any time
$D(t)$ = total compliance at any time
D_o = instantaneous compliance
t = loading time
a, m = materials regression coefficients

2.4.6 Repeated load-creep recovery

To assess permanent deformation characteristics of the mixtures, the repeated load-creep recovery triaxial test was performed according to the general procedure described in Witczak et al. (2002). The specimen preparation procedure was the same as for the static load-creep test. The confined test was selected to more closely represent field conditions, with a confining stress of 276 kPa (40 psi) and deviator stress of 1380 kPa (200 psi) recommended by Rushing (2013). The haversine load pulse consisted of a loading period of 0.1 s and a dwell time of 0.9 s. The test temperature was 43°C (109°F) to match the target temperature in the full-scale traffic tests described in Mejías-Santiago et al. (2013).

From the repeated load-creep recovery test data, 4 parameters are determined; they are summarized here with additional details of the data reduction process provided in Rushing (2013). The first two parameters are flow number (FN) and tertiary flow number (TF). In addition, the rate of accumulated permanent deformation can be mathematically expressed using the classic power-law model in Equation 3. The regression coefficients for intercept (a) and slope (b) are repeated load-creep recovery test outputs.

$$\varepsilon_p = a \times N^b \quad (3)$$

where:

ε_p = permanent strain
N = number of load cycles
a, b = regression constants

2.4.7 Dynamic modulus

To assess the overall stiffness of the mixtures, dynamic modulus (E^*) testing was performed in accordance with AASHTO standard method TP 62. The

specimen preparation procedure was the same as for the static loadcreep and the repeated load-creep recovery tests. Testing was only performed for the three highest recommended test temperatures of 21, 37, and 54°C, since high temperature rutting performance was of primary interest in this study. The six test frequencies were 25, 10, 5, 1, 0.5, and 0.1 Hz for a total of 18 test combinations.

Reduction of the test data was conducted in accordance with AASHTO standard practice PP 62 to develop dynamic modulus master curves to enable material characterization on a single response scale of reduced frequency at a reference temperature (Equation 4). The time-temperature superposition principle was used to shift measured data to a reference temperature of 70°F (21°C) by Equation 5. E^* data were shifted to the reduced frequency by using Equation 6. To determine the fitting coefficients $\alpha, \beta, \delta, \gamma, a_1$, and a_2, the Microsoft Excel solver function was used to minimize the error between the predicted and actual dynamic modulus measurements (Equation 7).

$$\log\left|E^*\right| = \delta + \frac{(\alpha)}{1 + e^{\beta + \gamma \log f_r}} \tag{4}$$

where:

$|E^*|$ = dynamic modulus (psi)
$\alpha, \beta, \delta, \gamma$ = fitting coefficients
f_r = reduced frequency (Hz)

$$\log f_r = \log f + a_1\left(T_R - T\right) + a_2\left(T_R - T\right)^2 \tag{5}$$

f = loading frequency at test temperature
a_1, a_2 = fitting coefficients
T_R = reference tempeature (°F)
T = test temperature (°F)

$$\log\left|\hat{E}^*\right| = \delta + \frac{(\alpha)}{1 + e^{\beta + \gamma\left[\log f + a_1(T_R - T) + a_2(T_R - T)^2\right]}} \tag{6}$$

$$\sum error^2 = \sum_1^n \left(\log\left|\hat{E}^*\right|_i - \log\left|E^*\right|_i\right)^2 \tag{7}$$

3 Phase 1 Test Results and Analysis

3.1 Overview of Phase 1 data collected

During Phase 1, data were collected as shown in Table 5 with the numbers indicating the number of specimen replicates tested. Binder grading was not performed for the foam processes since the foaming action is temporary and cannot be measured by regular binder testing. Tests for TSR, Hamburg wheel tracking, and APA wheel tracking at the LC-1 condition were conducted for all the mixtures. The other tests were only conducted for Mixtures 1 to 4, which were later produced during Phase 2 and tested under full-scale traffic, as described in Mejías-Santiago et al. (2013).

Table 5. Experimental test matrix and replication for LPLC Phase 1.

Mix ID	Binder PG	TSR	HLWT	APA LC-1 64°C	APA LC-2 43°C	Dynamic Modulus	Flow Number	Flow Time
1	1	1	4	2	4	3	3	3
2	1	1	4	2	4	3	3	3
3	1	1	4	2	4	3	3	3
4	NT	1	4	2	4	3	3	3
4a	NT	1	4	2	NT[a]	NT[a]	NT[a]	NT[a]
5	1	1	4	2	NT[a]	NT[a]	NT[a]	NT[a]
6	1	1	4	2	NT[a]	NT[a]	NT[a]	NT[a]
7	1	1	4	2	NT[a]	NT[a]	NT[a]	NT[a]
8	1	1	4	2	NT[a]	NT[a]	NT[a]	NT[a]
9	1	1	4	2	NT[a]	NT[a]	NT[a]	NT[a]
10	1	1	4	2	NT[a]	NT[a]	NT[a]	NT[a]
11	1	1	4	2	NT[a]	NT[a]	NT[a]	NT[a]
12	NT	1	4	2	NT[a]	NT[a]	NT[a]	NT[a]

a) NT - Not tested.

3.2 Asphalt binder

Table 6 provides binder test data at consistent temperatures and the continuous PGs of the binders; raw binder test data are located in Table A6 of the appendix. The foam process binders (4 and 12) were not tested, since the foaming is a transient effect and the water does not remain in the binder. Figure 3 presents the continuous PG data for the binders with data grouped by WMA process type.

Table 6. Summary of Phase 1 binder test data.

Binder ID	Original	RTFO Residue	PAV Residue			Continuous PG	
	G*/sin δ	G*/sin δ	G*sin δ	Stiffness	m-value	High Temp	Low Temp
	(kPa)[a]	(kPa)[a]	(kPa)[b]	(MPa)[c]	(—)[c]	(°C)	(°C)
1	0.766	1.68	4640	233	0.319	67.8	-23.9
2	1.51	2.62	5600	215	0.284	71.4	-18.3
3	0.811	1.63	4800	219	0.310	67.7	-22.9
4	NT[d]	NT[d]	NT[d]	NT[d]	NT[d]	NT[d]	NT[d]
5	0.689	1.46	4930	202	0.292	66.9	-18.6
6	1.52	2.39	5800	256	0.321	70.7	-23.4
7	0.760	1.27	5080	200	0.281	64.9	-16.3
8	1.14	1.94	4830	207	0.343	69.0	-24.7
9	0.691	1.64	5050	212	0.280	67.0	-17.6
10	2.75	5.88[e]	5890	217	0.279	81.9	-18.1
11	0.667	1.48	4890	232	0.322	66.7	-24.2
12	NT[d]	NT[d]	NT[d]	NT[d]	NT[d]	NT[d]	NT[d]

a) Tested at 70°C.

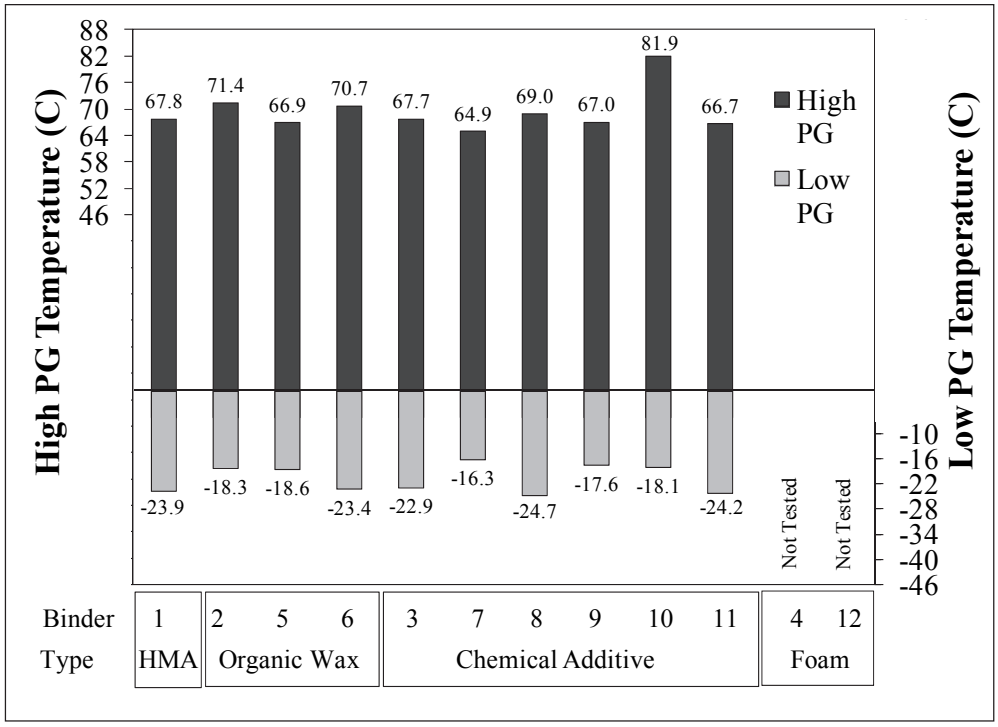
b) Tested at 25°C.

c) Tested at -12°C.

d) Not tested (NT).

e) Extrapolated from test data.

Figure 3. Phase 1 binder continuous PG data.



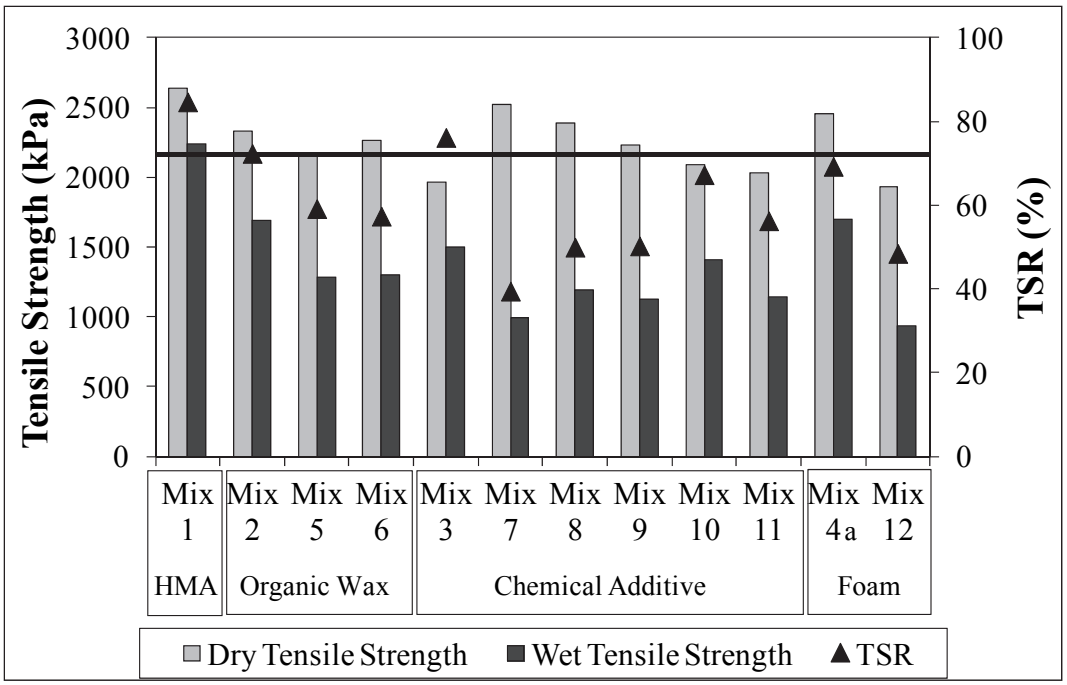
On the low temperature side, the base binder (Binder 1) was graded at -23.9°C, which slightly exceeds the specification of -22°C. Low PG temperatures for the WMA binders fall into two groups. The first group did not change much from the base binder and still meets the desired specification; this group includes one organic wax (Binder 6) and three chemical additives (Binders 3, 8, and 11). The second group changed markedly from the base binder with a temperature increase on the order of one full binder grade (i.e., 6°C increment). This group includes two organic waxes (Binders 2 and 5) and three chemical additives (Binders 7, 9, and 10). Overall, five of the nine WMA binders tested had a noticeable increase in low PG temperature, which could be indicative of reduced low temperature performance. However, note that the RTFO component of binder testing, which is intended to simulate the effect of HMA mixture production temperatures, was not modified to address the differences in temperature between HMA and WMA mixture production temperatures. Therefore, no certainty can be made from these data alone if the final mixture low-temperature performance would be detrimentally affected. Previous work has not indicated a reduction in low-temperature performance for WMAs made with the same modifiers as Binders 2, 3, and 4 in this study (Mejías-Santiago et al., 2012).

On the high temperature side, the base binder (Binder 1) was graded at 67.8°C, which slightly exceeds the specification of 67°C. The WMA binders, except for Binders 7 and 10, did not change appreciably from the base binder and generally still meet the desired specification. The high PG temperature for Binder 7 dropped about 3°C from that of the base binder, but it would still meet requirements for a PG 64 binder, so a major reduction in rutting performance would not be expected. The high PG temperature for Binder 10 increased dramatically compared to the base binder, over two full binder grades, and it essentially grades as a PG 82, which would typically be a polymer-modified binder. No apparent problems with the test data were observed, and project resource constraints prevented the binder from being re-tested to verify the results. Overall, the high temperature PG binder data do not indicate that a big reduction in rutting performance should be anticipated; however, the change in temperatures during mixture production previously discussed could affect final rutting performance.

3.3 Tensile strength ratio

Figure 4 presents Phase 1 TSR moisture damage results; raw data are located in Tables A7 and A8 of the appendix. The UFGS 32-12-15 specification requires a minimum TSR value of 75%. This criterion is shown as a horizontal line in Figure 4, where the vertical axis for TSR values is on the right. Only the HMA and WMA Mixture 3 had TSR values above the minimum threshold. TSR values for WMA were lower than for HMA in all cases, a finding consistent with previous studies. The category of WMA technology did not appear to influence the magnitude of TSR reduction. Likely, the performance of any given WMA additive relative to HMA could be different for a different aggregate and binder combination. The key point is that in most cases, WMA had noticeably lower and below specification TSR values that could be indicative of moisture susceptibility.

Figure 4. Phase 1 tensile strength and TSR data.

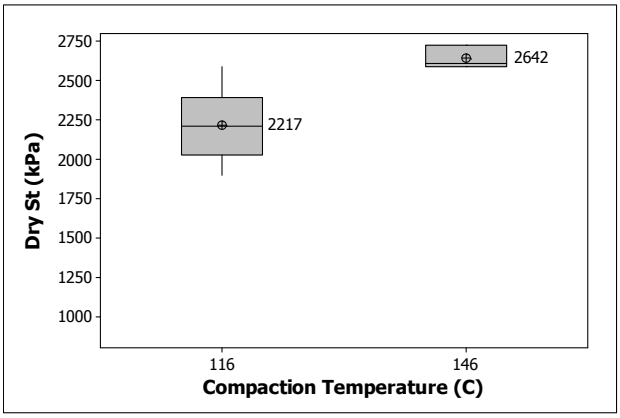


One potential explanation for lower TSR values of WMA is that the lower mixture temperatures result in less stiffening of the binder. If this is so, then the unconditioned (i.e., dry) tensile strengths (S_t) will be lower for WMA than for HMA of the same mixture. Box plots and an analysis of variance (ANOVA) with Tukey multiple comparison procedures were utilized in a statistical analysis of the tensile-strength data collected in this project (Figure 5). When data are grouped by mixture temperature (Figure 5a), the mean dry S_t of WMA mixture is 425 kPa (62 psi) lower than of HMA – a

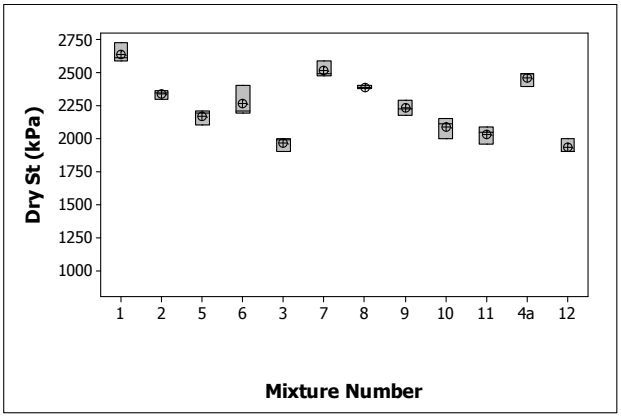
statistically significant difference. When the data for each mixture are investigated separately (Figure 5b), the only statistically conclusive result is also that HMA is stronger than WMA. Data for all the WMA mixtures were chained together and the WMA categories were all the same.

The same analysis was performed for conditioned (i.e., wet) tensile strengths in Figures 5c and 5d. The mean S_t of WMA was 940 kPa (136 psi) lower than of HMA – another statistically significant difference. The difference between WMA and HMA is more than twice as large for wet specimens as for dry specimens. Based on these data, some reduction in tensile strength can be attributed to the temperature change alone; still, additional damage occurs in the wet specimens of WMA relative to what occurs in HMA.

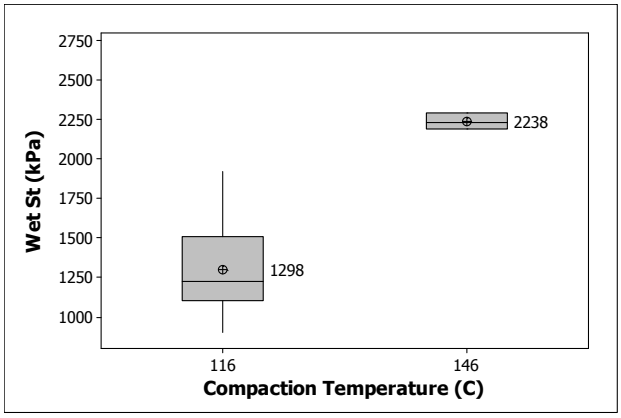
Figure 5. Analysis of tensile strength results.



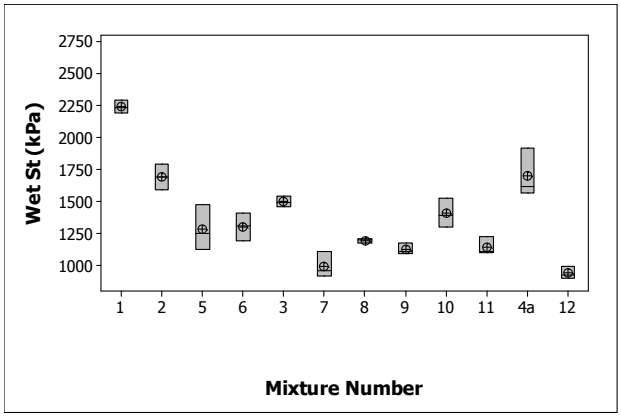
(a) Dry S_t by temperature



(b) Dry S_t by mixture number



(c) Wet S_t by temperature

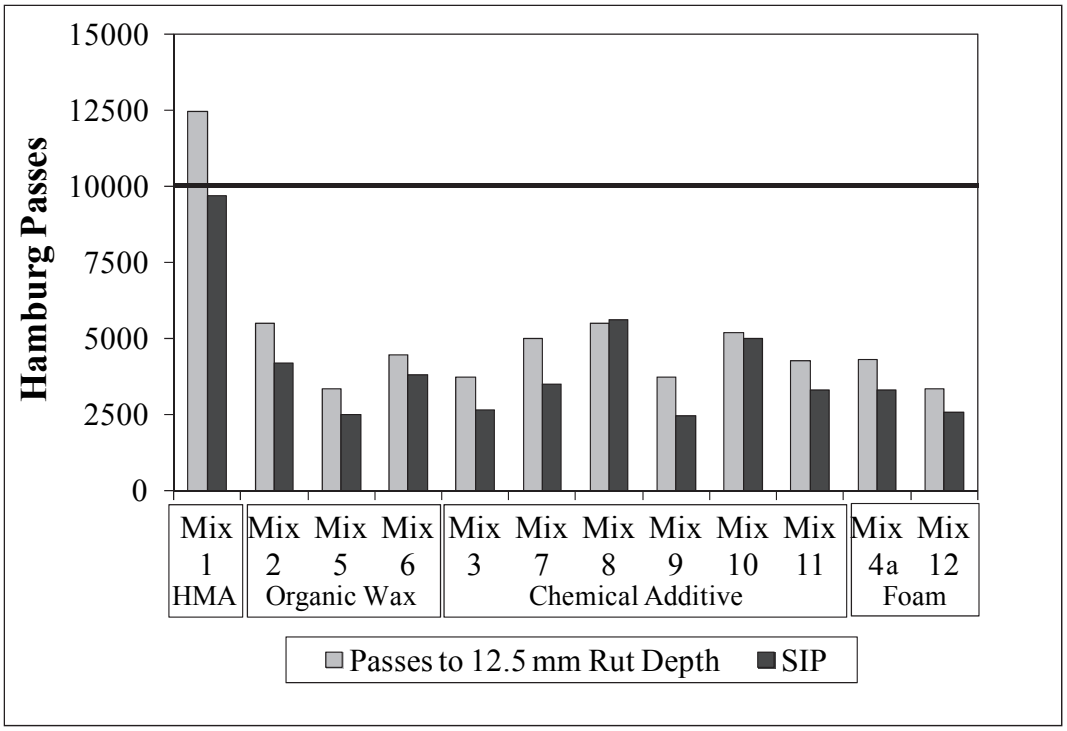


(d) Wet S_t by mixture number

3.4 Hamburg wheel tracking

Figure 6 presents Phase 1 Hamburg results for number of passes to achieve a 12.5-mm rut depth ($P_{12.5}$) and the number of passes to reach the stripping inflection point (SIP); raw data are located in Table A9 of the appendix. SIP is the number of wheel passes at which moisture damage starts to control performance and is calculated according to the test method. The Texas DOT (TxDOT) uses a threshold criterion of a minimum of 10,000 passes for $P_{12.5}$ for PG 64 binders, and Aschenbrener et al. (1994) reported that SIP values lower than 10,000 passes indicated moisture susceptibility. This threshold is shown in Figure 6 as a horizontal line. In general, both SIP and $P_{12.5}$ provide the same rankings of mixtures. The HMA mix exceeds the TxDOT threshold and has an SIP of nearly 10,000 passes, likely indicating acceptable moisture damage performance. Results indicated WMA had a considerable reduction in performance relative to HMA, potentially indicating an increase in moisture susceptibility. These results are consistent with the TSR results discussed previously. No trends indicating the influence of the technology category on the Hamburg results were observed, and the performance of any specific product could be different for a different aggregate or binder.

Figure 6. Phase 1 Hamburg wheel tracking test results.



3.5 APA wheel tracking

Figure 7 presents Phase 1 APA rutting results for LC-1 tested at 64°C with specimen air voids of 4±0.5%; raw data are located in Table A10 of the appendix. Rushing et al. (2012) recommended a threshold criterion of a minimum 4,000 cycles to achieve 10 mm of rutting for airfield mix acceptance when tested using a 1113 N (250 lb) wheel load and 1724 kPa (250 psi) hose pressure on 4% air void specimens. This threshold is shown in Figure 7 as a horizontal line. The data show that the HMA mix performs at the recommended threshold. Of the WMA mixtures, only Mixture 2 and Mixture 10 had rutting performance equivalent to or better than the HMA. The remaining WMA technologies resulted in an increase in APA rutting that ranged from 30 to 140%, as compared to HMA. The increase in rutting appears to be related to individual products rather than a technology category. A possibility is that the performance of any given WMA relative to HMA could be different for a different combination of aggregate and binder. The key observation is that WMA in general had increased rutting relative to HMA.

Figure 7. Phase 1 APA results for LC-1 tested at 64°C.

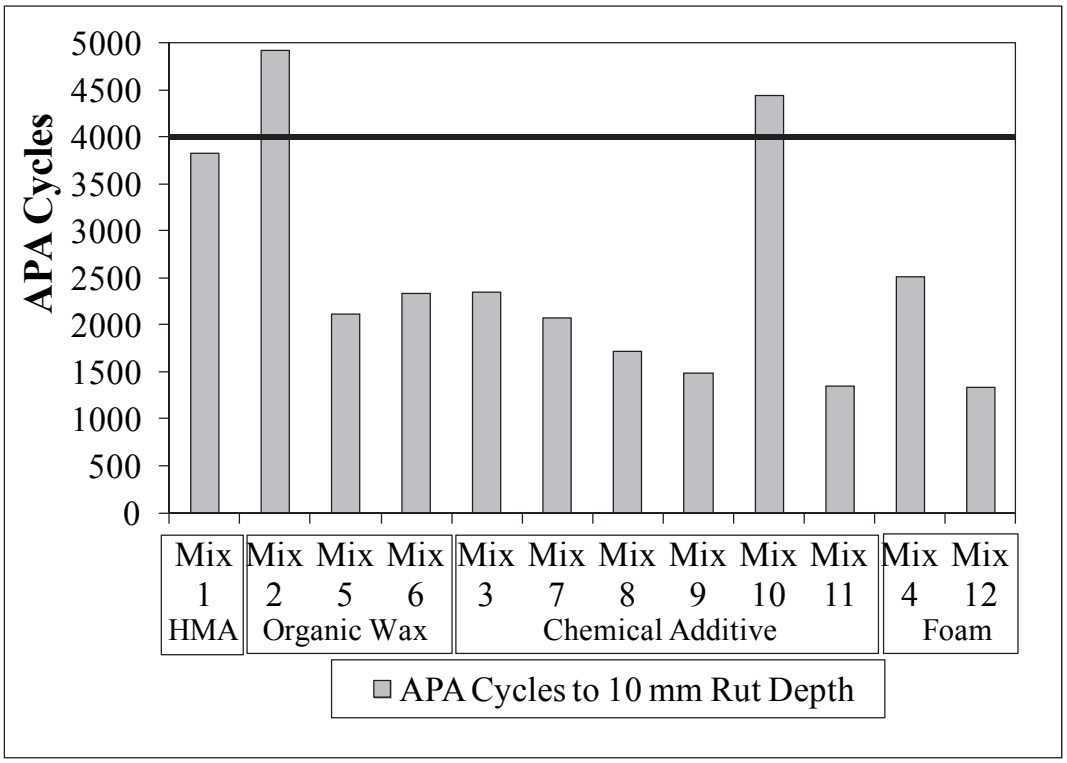
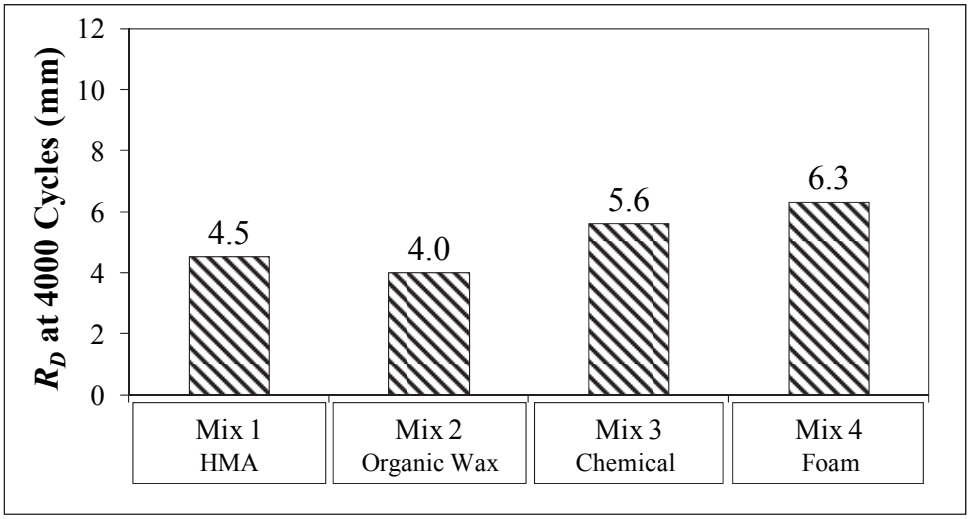


Figure 8 presents APA rutting results for LC-2 tested at 43°C with specimen air voids of 7±0.5%; raw data are located in Table A10 of the appendix. Rut depths (R_D) are reported at 4,000 cycles and are generally low. The Sasobit® WMA (Mix 2) was slightly better performing than the HMA (Mix 1), while the Evotherm™ (Mix 3) and foamed asphalt (Mix 4) WMAs did not perform quite as well as HMA. These relative performance results match those in Figure 7 for different APA test conditions.

Figure 8. Phase 1 APA results for LC-2 tested at 43°C.



3.6 Static load-creep

Table 7 summarizes the static load-creep test results. For airfield applications and these test conditions, Rushing and Little (2013) suggested that m be less than 0.45 or that FT be greater than 30 to ensure good rutting performance. Values for the HMA indicate the mixture is at the margin of the suggested performance test criteria. The average FT and TF values for the WMAs are lower than for the HMA, and average slope coefficient (m) values for the WMAs are higher than the HMA.

An ANOVA and Tukey multiple comparison procedure were performed of the data at the 5% significance level. Results were inconclusive for the coefficients a and m. For both FT and TF, the WMAs were statistically significantly lower than the HMA but were not statistically different from each other. However, these data alone do not make it clear if the difference will result in a meaningful reduction in mixture rutting performance.

Table 7. Phase 1 static load-creep results.

Mixture ID	Replicate	V_a	*a*	*m*	FT	TF
1 (HMA)	1	3.9	0.469	0.4371	33	64
	2	4.4	0.3912	0.4282	46	86
	3	4.2	0.3536	0.4982	37	69
	Avg.	**4.2**	**0.4046**	**0.4545**	**39**	**73**
2 (Sasobit®)	1	4.0	0.4301	0.4873	31	52
	2	4.0	0.4788	0.4879	24	49
	3	4.1	0.4049	0.464	29	60
	Avg.	**4.0**	**0.4379**	**0.4797**	**28**	**54**
3 (Evotherm™)	1	4.0	0.0205	0.5793	20	43
	2	4.0	0.4373	0.5064	20	43
	3	4.0	0.4061	0.5361	19	41
	Avg.	**4.0**	**0.2880**	**0.5406**	**20**	**42**
4 (Foam)	1	4.3	0.3894	0.5163	19	46
	2	4.8	0.4307	0.507	23	45
	3	4.3	0.4029	0.5099	24	45
	Avg.	**4.5**	**0.4077**	**0.5111**	**22**	**45**

3.7 Repeated load-creep recovery

Table 8 summarizes the repeated load-creep recovery test results. For airfield applications and these test conditions, Rushing and Little (2013) suggested that *m* be less than 0.45 or that FN be greater than 200 to ensure good rutting performance. Values for the HMA indicate the mixture is at the margin of the suggested performance test criteria. The average FN and TF values for the WMAs are lower than for the HMA, and average slope coefficient (*m*) values for the WMAs are similar to or higher than the HMA.

An ANOVA and Tukey multiple comparison procedure were performed with the data at the 5% significance level. Results were inconclusive for the coefficients *a* and *m*. For FN, the Evotherm™ and foamed asphalt WMAs were statistically significantly lower than the HMA but were not statistically different from each other; the Sasobit® WMA could not be distinguished from either HMA or the other WMAs. For TF, the Evotherm™ and foamed asphalt WMAs were statistically significantly lower than the HMA and the Sasobit® WMA. However, it is not clear from these data alone if the difference will result in a meaningful reduction in mixture rutting performance.

Table 8. Phase 1 repeated load-creep recovery results.

Mixture ID	Replicate	V_a	*a*	*m*	FN	TF
1 (HMA)	1	4.0	0.2397	0.4612	159	400
	2	4.2	0.2600	0.4071	183	495
	3	4.0	0.2338	0.4461	164	419
	Avg.	**4.1**	**0.2445**	**0.4381**	**169**	**438**
2 (Sasobit®)	1	3.8	0.2744	0.4292	147	371
	2	4.0	0.2258	0.4447	170	450
	3	3.8	0.2239	0.4467	141	371
	Avg.	**3.9**	**0.2414**	**0.4402**	**153**	**397**
3 (Evotherm™)	1	3.9	0.1369	0.5967	98	262
	2	4.0	0.2469	0.4737	106	276
	3	4.1	0.2189	0.5020	101	271
	Avg.	**4.0**	**0.2009**	**0.5241**	**102**	**270**
4 (Foam)	1	4.1	0.1738	0.5390	95	256
	2	4.3	0.2407	0.4666	110	297
	3	4.4	0.2345	0.4787	110	295
	Avg.	**4.2**	**0.2163**	**0.4948**	**105**	**283**

3.8 Dynamic modulus

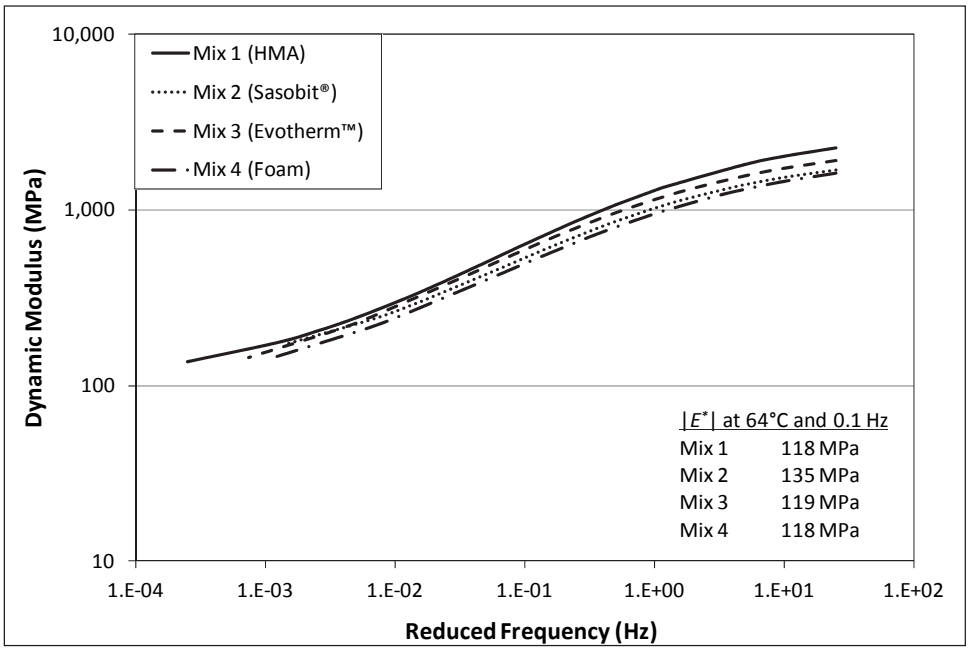
Raw $|E^*|$ test data are located in Table A11 through Table A14 of the appendix. Master curves for each mixture were developed and are shown in Figure A1 through Figure A4 of the appendix. Table 9 summarizes the dynamic modulus master curve fitting parameters for Equation 4 and Equation 5. The AASHTO TP 62 procedure suggests that for a good quality fit of the master curve equations to the data, the ratio of S_e to S_y should be less than 0.05 and the explained variance should exceed 0.99. All four master curves in Table 9 meet or exceed these criteria.

Figure 9 shows all four master curves for the Phase 1 laboratory-produced mixture. In general, the HMA mixture provides the greatest stiffness at a given reduced frequency, with the WMAs rank as Evotherm™, Sasobit®, and foamed asphalt in decreasing order of stiffness. At lower reduced frequencies (i.e., higher temperatures and/or slower loading rates), the stiffness differential between the mixtures is smaller than at the higher reduced frequencies.

Table 9. Phase 1 |*E**| master curve parameters.

Fitting	Mixture Number			
Parameter	1 (HMA)	2 (Sasobit®)	3 (Evotherm™)	4 (Foam)
α	1.4766	1.3028	1.4979	1.4329
β	-1.1276	-1.1370	-1.2300	-1.1072
δ	4.1558	4.1838	4.0612	4.0604
δ	-0.9301	-0.9750	-0.8902	-0.8876
a_1	0.0439	0.0202	0.0394	0.0310
a_2	8.018E-06	-1.787E-04	6.559E-05	-1.516E-05
S_e / S_y	0.0301	0.0090	0.0067	0.0082
Explained Variance	0.9994	0.9999	1.0000	1.0000

Figure 9. Phase 1 |E*| master curves.



For airfield applications and these test conditions, Rushing and Little (2013) suggested that the value of $|E^*|$ at the PG high temperature (i.e., 64°C) and 0.1 Hz loading frequency should be greater than 124 MPa to ensure good rutting performance. Based on this criterion, the HMA, Evotherm™ and foamed asphalt mixtures show essentially equivalent performance that is slightly below the recommended minimum (values are provided in Figure 9), while the Sasobit® mixture has somewhat better performance and meets the recommended minimum criterion. Overall, the $|E^*|$ data do not suggest that a dramatic reduction in mixture rutting performance should be expected for the WMAs relative to the HMA.

4 Phase 2 Test Results and Analysis

4.1 Overview of Phase 2 data collected

During Phase 2, data were collected as shown in Table 10 with the numbers indicating the number of specimen replicates tested; APA data are further detailed in Table 11. Asphalt binder was extracted and recovered from mixture samples and tested for PG. During production, sampled material was used to compact test specimens in the laboratory without the mixture being allowed to cool off (i.e., no reheating of mixture). Specimens for APA testing were produced at two air void levels for two load case and temperature combinations. Specimens were also produced with reheated material to assess the effects of the reheating on mixture Hamburg and APA performance properties. TSR specimens were only produced with reheated PPLC specimens; testing resource limitations did not allow for TSR testing on mixtures without reheating. The Phase 2 mixtures were used to construct pavement test sections at the Hangar 4 test facility at ERDC at which the pavement was exposed to air and ambient temperatures but not exposed to direct sunlight or rain.

Table 10. Experimental test matrix and replication for Phase 2.

Preparation Method	Time of Coring	Mix ID	Binder Performance Grade	Tensile Strength Ratio	Hamburg Wheel Tracking	Dynamic Modulus	Repeated Load-Creep Recovery	Static Load-Creep
PPLC no reheat	---[a]	1	1	---[a]	4	---[a]	---[a]	---[a]
		2	1	---[a]	4	---[a]	---[a]	---[a]
		3	1	---[a]	4	---[a]	---[a]	---[a]
		4	1	---[a]	4	---[a]	---[a]	---[a]
PPLC reheat	---[a]	1	---[a]	1	4	3	2	2
		2	---[a]	1	4	3	2	2
		3	---[a]	1	4	3	2	2
		4	---[a]	1	4	3	2	2
PPFC	< 1 week after placement	1	---[a]	---[a]	4	---[a]	---[a]	---[a]
		2	---[a]	---[a]	4	---[a]	---[a]	---[a]
		3	---[a]	---[a]	4	---[a]	---[a]	---[a]
		4	---[a]	---[a]	4	---[a]	---[a]	---[a]

a) Dashes indicate not applicable or experimental combination not tested.

Table 11. APA test matrix and replication for Phase 2.

Preparation Method	Time of Coring	Mix ID	LC-1			LC-2			
			64°C	64°C	64°C	43°C	43°C	37°C	49°C
			4% V_a	7% V_a	Field V_a	7% V_a	Field V_a	Field V_a	Field V_a
PPLC no-reheat	---[a]	1	4	4	---[a]	4	---[a]	---[a]	---[a]
		2	4	4	---[a]	4	---[a]	---[a]	---[a]
		3	4	4	---[a]	4	---[a]	---[a]	---[a]
		4	4	4	---[a]	4	---[a]	---[a]	---[a]
PPLC reheat	---[a]	1	2	4	---[a]	4	4	4	4
		2	2	4	---[a]	4	4	4	4
		3	2	4	---[a]	4	4	4	4
		4	2	4	---[a]	4	4	4	4
PPFC	< 1 week after placement	1	---[a]	---[a]	4	---[a]	---[a]	---[a]	---[a]
		2	---[a]	---[a]	4	---[a]	---[a]	---[a]	---[a]
		3	---[a]	---[a]	4	---[a]	---[a]	---[a]	---[a]
		4	---[a]	---[a]	4	---[a]	---[a]	---[a]	---[a]
PPFC	4 weeks after placement	1	---[a]	---[a]	---[a]	---[a]	4	---[a]	---[a]
		2	---[a]	---[a]	---[a]	---[a]	4	---[a]	---[a]
		3	---[a]	---[a]	---[a]	---[a]	4	---[a]	---[a]
		4	---[a]	---[a]	---[a]	---[a]	4	---[a]	---[a]
PPFC	18 weeks after placement	1	---[a]	---[a]	4	---[a]	4	---[a]	---[a]
		2	---[a]	---[a]	4	---[a]	4	---[a]	---[a]
		3	---[a]	---[a]	4	---[a]	4	---[a]	---[a]
		4	---[a]	---[a]	4	---[a]	4	---[a]	---[a]
PPFC	32 weeks after placement	1	---[a]	---[a]	4	---[a]	4	4	4
		2	---[a]	---[a]	4	---[a]	4	4	4
		3	---[a]	---[a]	4	---[a]	4	4	4
		4	---[a]	---[a]	4	---[a]	4	4	4

a) Dashes indicate not applicable or experimental combination not tested.

Specimens of the compacted pavement were cored and tested in the Hamburg and APA. The APA coring intervals (Table 11) were selected with respect to the high temperature, accelerated traffic testing of the constructed test items described in Mejías-Santiago et al. (2013). Cores were taken before and after the accelerated traffic testing, which began about 20 weeks after construction; testing of all four test sections was complete by 32 weeks after construction. However, since only one section was tested at a time, each test section was held only at the elevated test

temperature for about 2 to 3 weeks total. There was some variation in the test temperature of full-scale testing, so cores were APA tested with LC-2 at three temperatures to assess the effects of temperature variation. Specimens of reheated mixture were also laboratory compacted to target the field air voids levels and tested with LC-2 at three test temperatures.

4.2 Asphalt binder and mixture

Table 12 provides binder test data at consistent temperatures and the continuous PGs of the binders; raw binder test data are located in Table A15. Figure 10 compares the continuous PG data for Binders 1 to 4 as original binder and as recovered binder from plant-produced mixture. On the low temperature side, the recovered Binders 1, 3, and 4 all grade similarly to each other and meet the requirement of -22°C. On the other hand, recovered Binder 2 does not quite meet the requirement. On the high temperature side, all recovered binders meet the 67°C requirement. Though Binder 3 is a few degrees lower than the others, major differences in rut performance of plant-produced material between the HMA and WMAs would not be anticipated based on these data.

Differences between original binder and recovered binder properties may be useful in estimating how the WMAs that were not plant produced (i.e., Binders 5 to 12) might have performed and consequently can improve the interpretation of laboratory performance test data for those mixtures. On the low temperature side (Figure 10), the original base binder graded at -23.9°C and the recovered HMA binder graded as -25.1°C, a not unreasonable difference of only 1.2°C. For the WMA Binders 2 and 3, the difference between original and recovered binders was 2.4°C and 0.9°C, respectively. So in general for low PG temperatures, the original binder testing was slightly or somewhat conservative relative to the recovered binder testing. On the high temperature side (Figure 10), the original base binder graded at 67.8°C, and the recovered HMA binder graded at 70.2°C, an increase of 2.4°C. For the WMA Binders 2 and 3, the difference between original and recovered binders was practically negligible at 0.5°C and -0.6°C, respectively. So in general for low PG temperatures, the original binder testing was similar to or somewhat conservative relative to the recovered binder testing.

Table 12. Summary of Phase 2 binder test data.

Binder ID	Recovered Binder	PAV Residue			Continuous PG	
	G*/sin δ (kPa)[a]	G*sin δ (kPa)[b]	Stiffness (MPa)[c]	m-value (—)[c]	High Temp (°C)	Low Temp (°C)
1	2.24	3600	147	0.324	70.2	-25.1
2	2.85	4230	184	0.288	71.9	-20.7
3	1.51	3500	150	0.338	67.1	-26.3
4	2.90	3820	149	0.317	72.2	-23.8

a) Tested at 70°C.

b) Tested at 25°C.

c) Tested at -12°C.

Figure 10. Original and recovered binder continuous PG data.

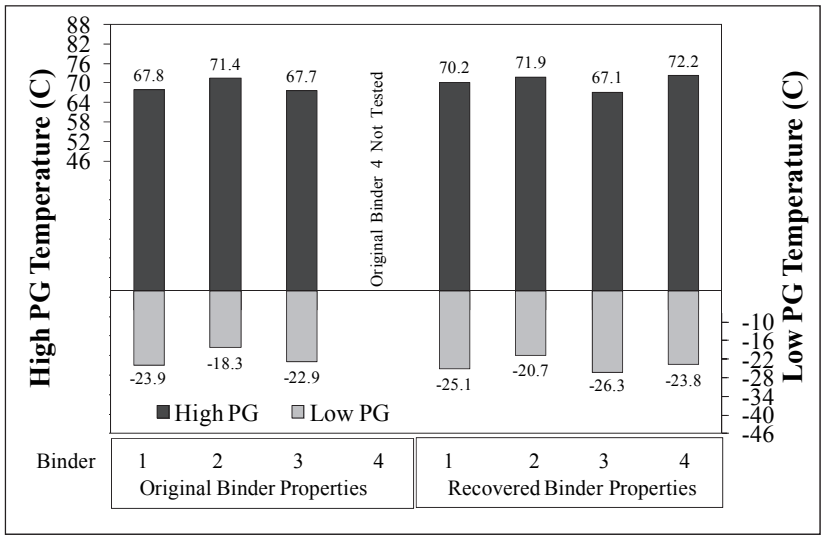
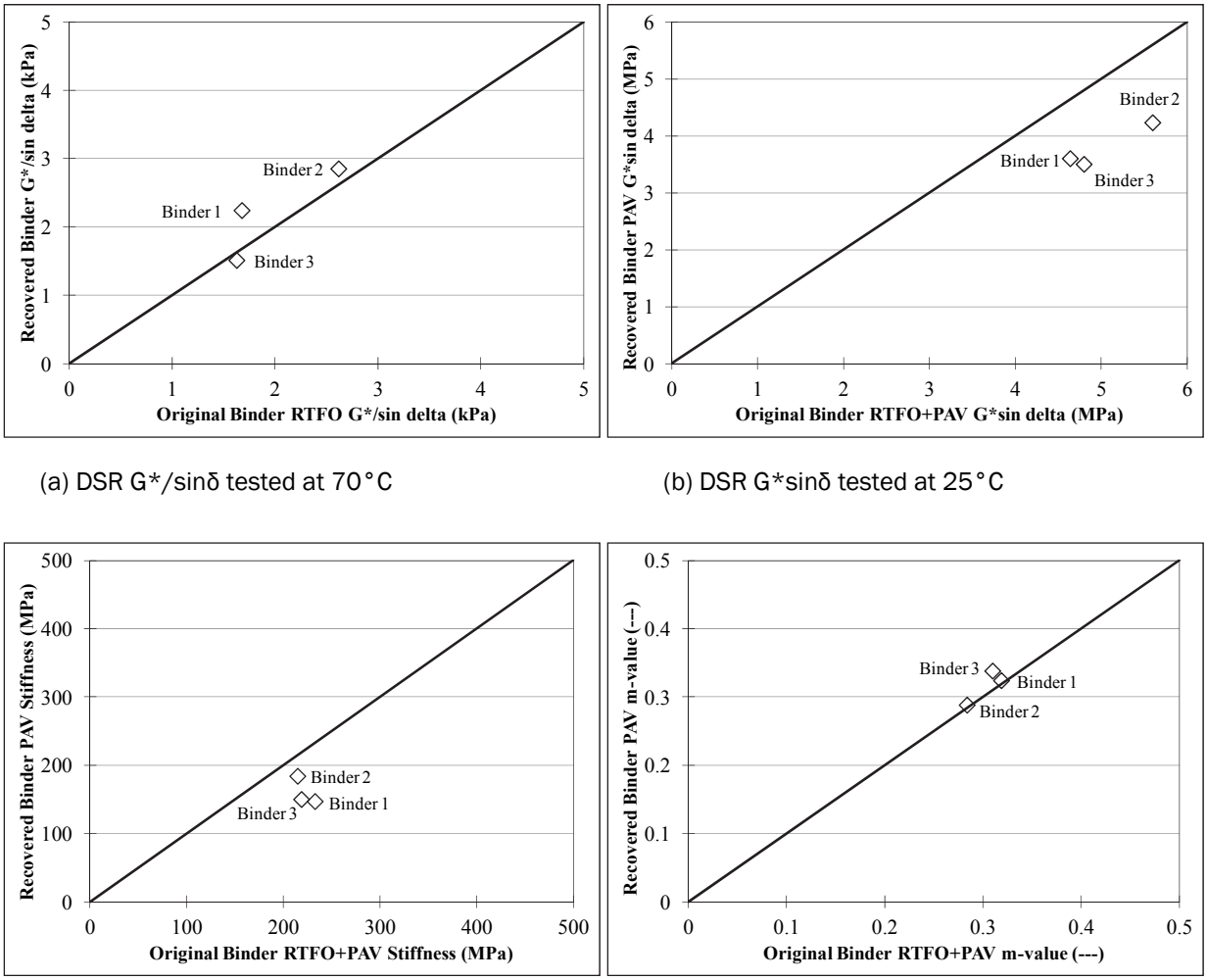


Figure 11 explores this topic further with equality plots of original binder and recovered binder test data at consistent test temperatures from Table 3. For the rutting parameter G*/sinδ (Figure 11a), the original binder RTFO residue for the WMAs provided a good estimate of the recovered binder values. Interestingly, values for the recovered HMA were slightly under-predicted by the RTFO residue. The RTFO procedure is intended to approximate the change in binder properties due to batch-plant mixing at about 150°C (AASHTO 2009). For the fatigue parameter G*sinδ (Figure 11b), the original binder RTFO residue over-predicted the recovered binder values. For the Bending Beam Rheometer (BBR) low temperature stiffness parameter (Figure 11c), the original binder RTFO+Pressure Aging Vessel (PAV) residue tended to over-predict the recovered binder values. For the BBR m-value parameter (Figure 11d), the original binder RTFO+PAV residue provided a good estimate of the recovered binder

properties. This is encouraging, since the m-value specification requirement controls the low PG temperature for most binders (Iliuta et al. 2004). These data suggest that the rutting parameter and controlling low temperature thermal cracking parameter of binder recovered from plant-produced material are reasonably approximated by tests of RTFO residue. This conclusion is limited, however, since only materials produced with one base binder by one specific plant were tested.

Figure 11. Original and recovered binder raw test data comparison.



(a) DSR G*/sinδ tested at 70°C

(b) DSR G*sinδ tested at 25°C

(c) BBR stiffness tested at -12°C

(d) BBR m-value tested at -12°C

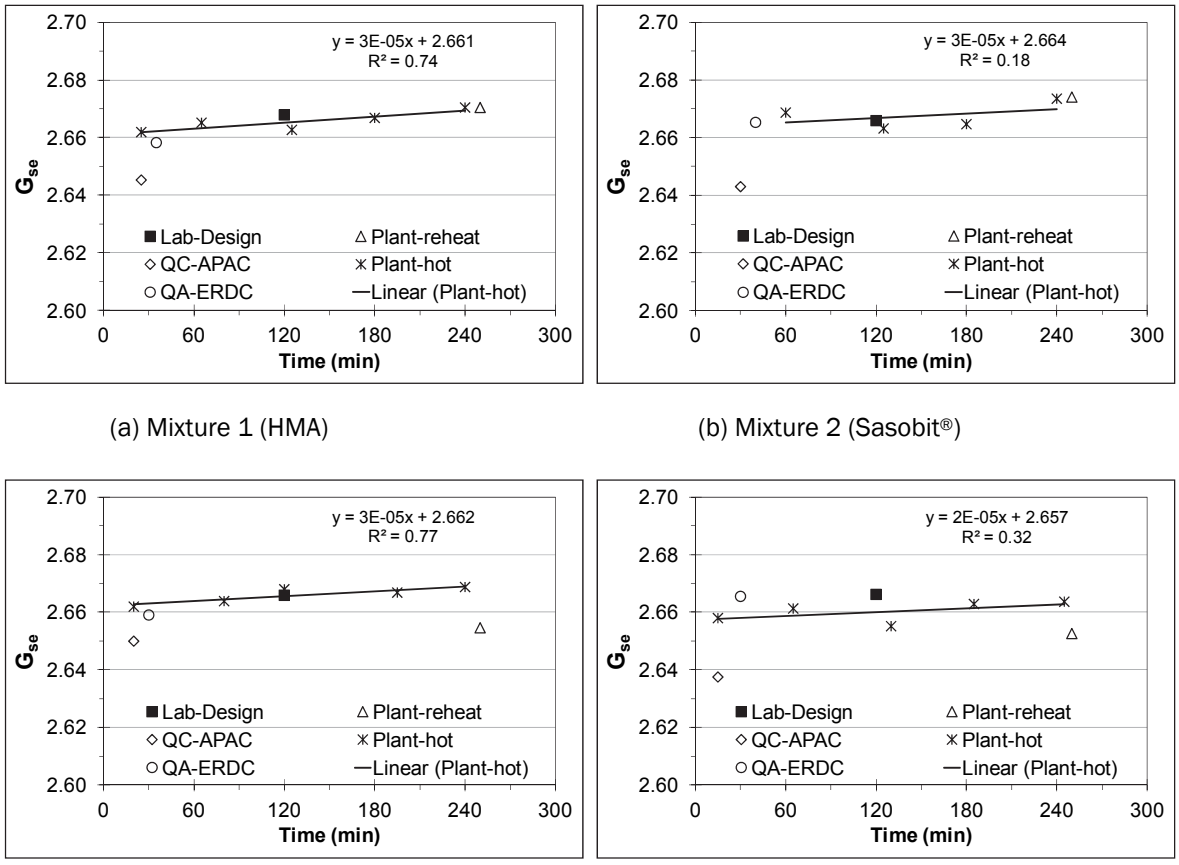
Samples of the plant-produced mixtures were kept hot in an oven for varying time periods before being cooled and tested for G_{mm} to investigate the variation in asphalt absorption with time. Mixture samples were taken from haul trucks at the asphalt plant concurrent with the QC samples; material for an initial G_{mm} test was allowed to cool. Additional material was kept hot in an oven set to the target compaction temperature, then

samples were removed from the oven at time periods of approximately 1, 2, 3, and 4 hours and allowed to cool for G_{mm} testing. Additional reheated material was also tested for $G_{mm.}$ Raw data for this testing is located in Table A16. Tested G_{mm} values and QC asphalt contents were then used to compute effective aggregate specific gravity (G_{se}) values. Figure 12 presents plots of these data for each mixture, where the x-axis denotes time after production to provide an overall picture of asphalt absorption with time. For a given aggregate source, an increase in G_{se} indicates an increase in binder absorbed by the aggregate. For each mixture, there was a general trend of slightly increasing G_{se} with time. Four additional G_{se} data points are provided on the plot for comparison: laboratory mix design, QC performed by the contractor, QA performed by the research team, and material that was allowed to fully cool and then reheated. In general, the laboratory mix design and research team QA data fall in line with the time-dependent data. The reheated data fall in line for Mixtures 1 and 2 but are slightly lower than expected for Mixtures 3 and 4. Overall, the contractor QC data fall below the expected value based on the other data; differences are likely due to procedural and operator differences between laboratories.

The time between Phase 2 plant production and placement of the test sections described in Rushing et al. (2013) was generally about 45 minutes but ranged from as little as 30 minutes to as much as 120 minutes. Based on Figure 12, the G_{se} increase for that time period (i.e., from 30 minutes to 120 minutes) is no more than 0.003, indicating that the increase in absorbed asphalt was slight. For this aggregate blend, that G_{se} increase translates to about a 0.04 increase in P_{ba}; for comparison, recall that the P_{be} tolerance in Phase 1 mix design was ±0.05. Overall, the data indicate that for these mixtures, the short haul times during full-scale production did not greatly affect the asphalt absorption and the quantity of absorbed asphalt anticipated from mix design was near the quantity obtained from plant production.

Each plant-produced mixture was reheated, and two specimens were compacted to measure volumetrics. The average air voids of these specimens were 2.6, 3.4, 2.0, and 2.1 for Mixtures 1 to 4, respectively. The average air voids of QA specimens of these mixtures compacted without reheating (data from Table 4) were 2.3, 3.1, 2.0, and 4.7 for Mixtures 1 to 4, respectively. The V_a value for mixture 4 of 4.7 is believed to be too high based on other data (e.g., the QC value was V_a = 1.9). The changes in air

Figure 12. Variation of G_{se} with time.



(a) Mixture 1 (HMA)

(b) Mixture 2 (Sasobit®)

(c) Mixture 3 (Evotherm™)

(d) Mixture 4 (foamed asphalt)

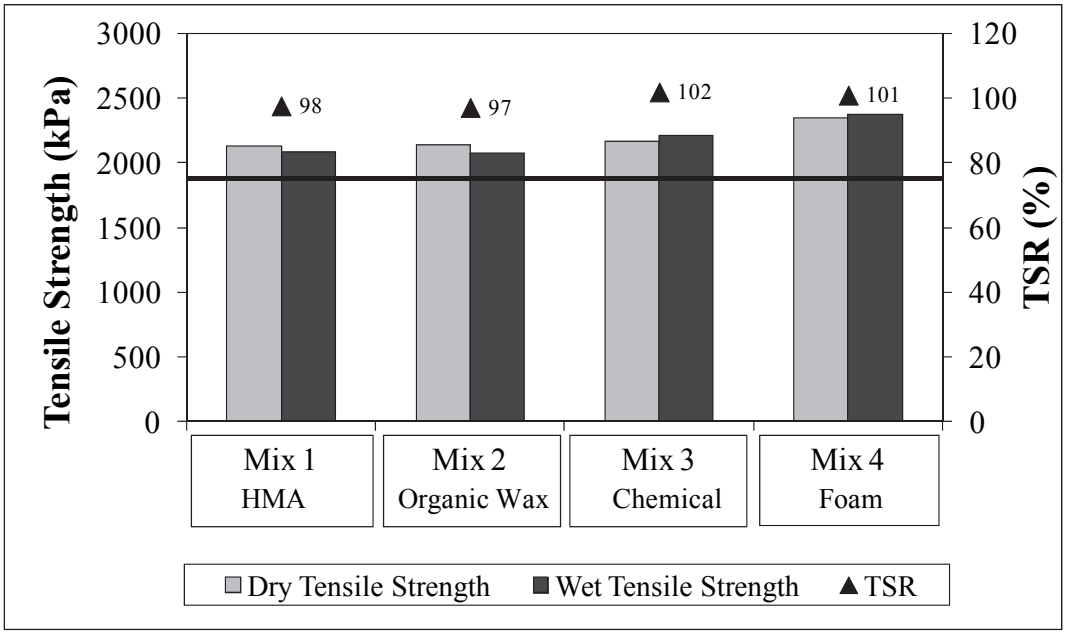
voids for reheated mixture relative to un-reheated mixture were +0.3, +0.3, 0.0, -2.6 for mixtures 1 to 4, respectively. Disregarding the value for Mixture 4, the difference in V_a due to mixture reheating was negligible. This result corresponds to that reported by Huner and Brown (2001), who observed that reheating and compaction of plant-produced asphalt mixtures compared to immediate compaction without re-heating had no significant effects on volumetrics when using SGC compaction.

4.3 Tensile strength ratio

TSR test results from plant-produced mixture are presented in Figure 13; raw data are located in Table A17. Results indicate similar performance for the HMA and three WMA mixes; the TSR values of all plant-produced mixtures were approximately 100% and greatly exceeded the minimum threshold of 75%, indicated by a horizontal line in Figure 13. No stripping was visually observed on these specimens. Improvements in the TSR likely resulted from increased production temperature from the laboratory to the

asphalt plant. Other researchers have observed that re-heating of plant-produced mixture produces better TSR moisture susceptibility results than for the same mixture when laboratory mixed and compacted without re-heating (Tunnicliff and Root, 1995). In general, TSR results for laboratory-produced mixture were not predictive of TSR results on reheated plant-produced material. Due to testing resource constraints, TSR testing was not performed on plant-produced material without reheating.

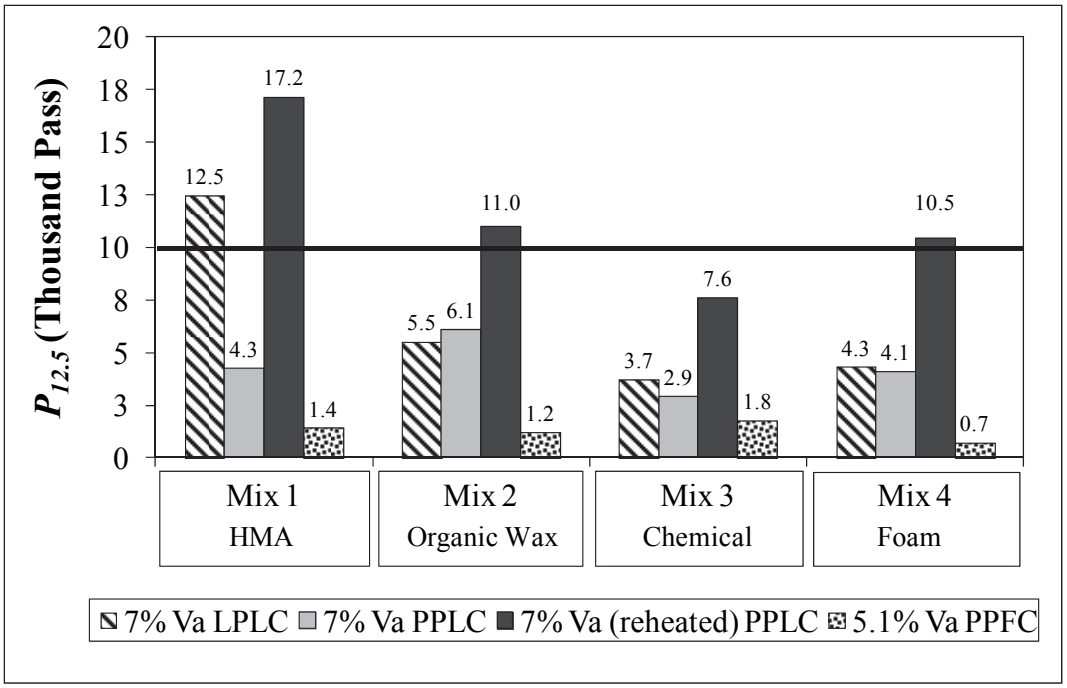
Figure 13. Phase 2 TSR results.



4.4 Hamburg wheel tracking

The raw Hamburg test data for Phase 2 is located in Table A18 to Table A20 of the appendix. Figure 14 presents Hamburg $P_{12.5}$ data for three different types of plant-produced mix samples: (1) PPLC samples compacted to 7% V_a while the mixture was still hot, (2) PPLC samples reheated and compacted to 7% V_a, and (3) PPFC samples collected from the test section (with an average V_a of 5%). The LPLC data from Phase 1 at 7% V_a are also included for reference. The horizontal line represents the TxDOT threshold of 10,000 passes for $P_{12.5}$. SIP data are not shown for brevity, since the previous Phase 1 data analysis showed that they closely follow $P_{12.5}$ data. SIPs were observed for all the laboratory-compacted mixtures, but not for the field-compacted mixtures, likely due to the early failure of those specimens.

Figure 14. Phase 2 Hamburg results.

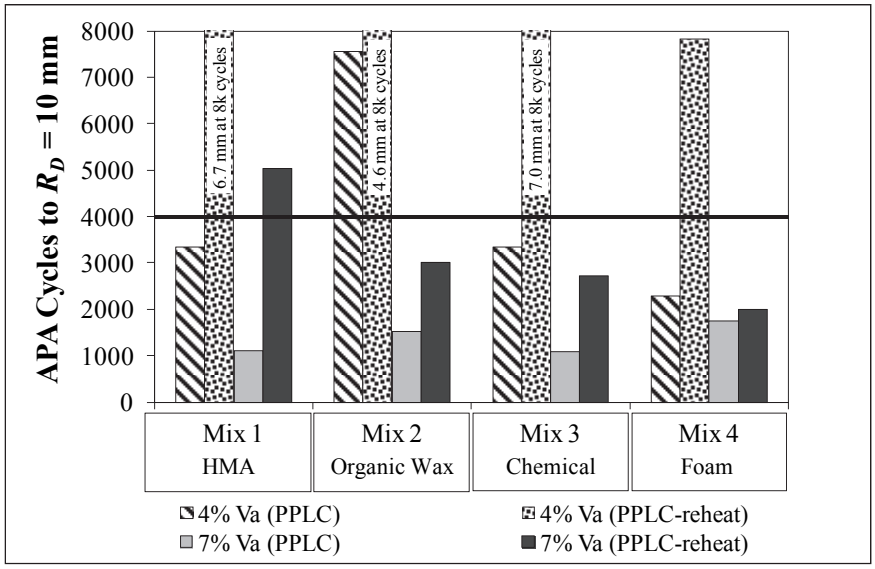


For the PPLC mixture without reheating, performance of the WMAs was comparable to the HMA. Performance of the PPLC mixture was greatly reduced from LPLC for HMA, but was comparable for the WMA mixtures. The HMA PPLC specimens compacted at 7% air voids had lower rutting resistance than the HMA LPLC specimens. This could be partly attributed to the short haul from the asphalt plant to the job site (≈20 minutes), which did not allow for enough binder aging as compared to the aging applied to the laboratory-produced mixtures (2 hours). When the plant mixture was reheated to produce additional PPLC samples, the rutting performance improved considerably as expected, due to the stiffening of the binder that occurred when it was exposed again to high temperatures. The WMA PPLC specimens performed similarly to the WMA LPLC specimens. However, when the mixture was re-heated, the performance improved, and two out of three warm mixtures met the rutting threshold. However, WMA still showed reduced performance compared to HMA. Specimens from field-compacted mixture performed very poorly compared to the rest of the samples for all mixes, including HMA. However, this is because these mixes failed early due to excessive rutting. The samples reached the test termination rut depth 12 mm (0.47 in.) before they experienced any deformation controlled by moisture damage indicated by evidence of an SIP. The PPFC specimens also exhibited similar performance of the WMAs and the HMA.

4.5 APA wheel tracking

Raw data for Phase 2 APA testing is located in Table A21 to Table A24 of the appendix. Discussion of the LC-1 results is provided first, followed by discussion of the LC-2 results. Performance of the mixtures varied considerably for differences in APA load cases, test temperatures, and compaction methods. As a result, it was not possible to use a single response variable to interpret all the data. APA data are therefore presented as either cycles to achieve a 10 mm rut depth (R_D) or R_D at 4,000 cycles based on the recommended specification criteria of Rushing et al. (2012).

Figure 15. Effect of plant-produced mixture reheating on APA LC-1 performance.



Using LC-1 data, the effects of reheating mixture before compaction on APA results were investigated using plant-produced material (Figure 15). Results are presented as cycles to R_D = 10 mm by target air void levels. The mixture was compacted either soon after sampling (i.e., without reheating) or was allowed to fully cool to room temperature and then reheated for compaction at a later time. A horizontal line at 4,000 cycles indicates the minimum performance criterion recommended by Rushing et al. (2012) for mixtures with approximately 4% V_a. For V_a = 4% data, only mixture 2 (Sasobit® WMA) reached the minimum criterion when compacted without reheating. Performance of the mixtures was noticeably improved when reheated before compaction; Mixtures 1 to 3 did not achieve 10 mm of rutting during the entire test. This result indicates that the reheating process affects rut development. Reheating mixture is expected to improve rutting performance because stiffening of the binder occurs during the additional

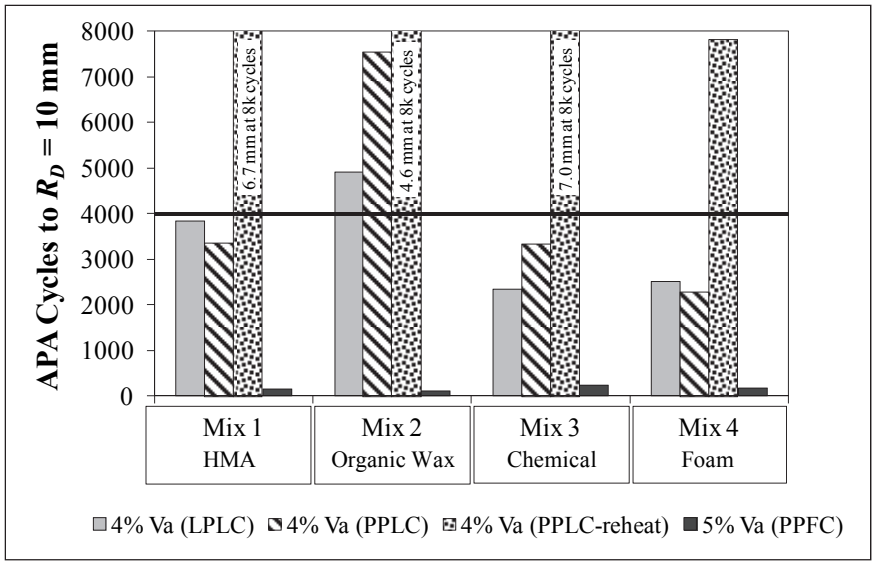
exposure to high temperatures. APA performance was improved by a factor of 3.4 to 5.9 when mixture was reheated before compaction. For V_a = 7% data, APA performance was improved by a factor of 1.1 to 4.6 when mixture was reheated before compaction. Mixture 1 (HMA) consistently had the greatest increase in APA performance for reheated mixture, while Mixture 4 (foamed asphalt WMA) consistently had the smallest increase. The increase in APA performance was less for higher air void specimens. For the PPLC data without reheating, performance of the WMA was generally similar to or better than HMA. For PPLC reheated data, WMA performance was similar to or worse than HMA.

Using LC-1 APA data, the effects of mixture production type (laboratory vs. plant), mixture reheating, and specimen compaction method (laboratory vs. field) are investigated in Figure 16. Results for four different data types are shown: (1) V_a = 4% LPLC specimens from Phase 1, (2) V_a = 4% PPLC specimens compacted with no mixture reheating, (3) V_a = 4% PPLC specimens compacted after mixture was reheated, and (4) PPFC specimens collected from the test section within 1 week of placement (with an average V_a of 5%). PPLC mix showed performance similar to LPLC mix for the HMA and foam but improved performance for the WMA mixes with chemical or wax additives. On the other hand, APA rut depths for PPFC mix exhibited very poor performance both in general and relative to laboratory-compacted mixture. The HMA and WMAs were all similar and ranged from 180 to 250 cycles. The reduction is a great deal more than would be expected for the small difference in air voids of the specimens. Literature sources have also reported greater rutting of field-compacted mixture than for laboratory-compacted mixture, though the reported differences were not as great. Sadasivam (2004) compared the permanent deformation resistance of four mixtures in the APA for field cores and for SGC-compacted specimens of plant-produced, re-heated mixture at the same air void level as the field cores. For all mixtures, rut depths of the field cores were 1.3 to 4.5 times higher than for SGC specimens (Sadasivam, 2004).

PPFC specimens for APA testing were cored from the test section at three different time periods: (1) less than 1 week after placement, (2) 18 weeks after placement and before accelerated traffic testing commenced, and (3) 32 weeks after testing once all traffic testing was complete. During the first 18 weeks after placement, the pavements experienced air exposure and the ambient temperatures of summer (mid-June to November); however, since the test items were located in a covered test facility, there was no

exposure to direct solar radiation (i.e., pavement was 100% shaded) or to rain. Between 18 and 32 weeks after placement (winter months of November to mid February), each pavement test section was exposed to an elevated temperature of approximately 43°C for two to three weeks while accelerated traffic testing was conducted.

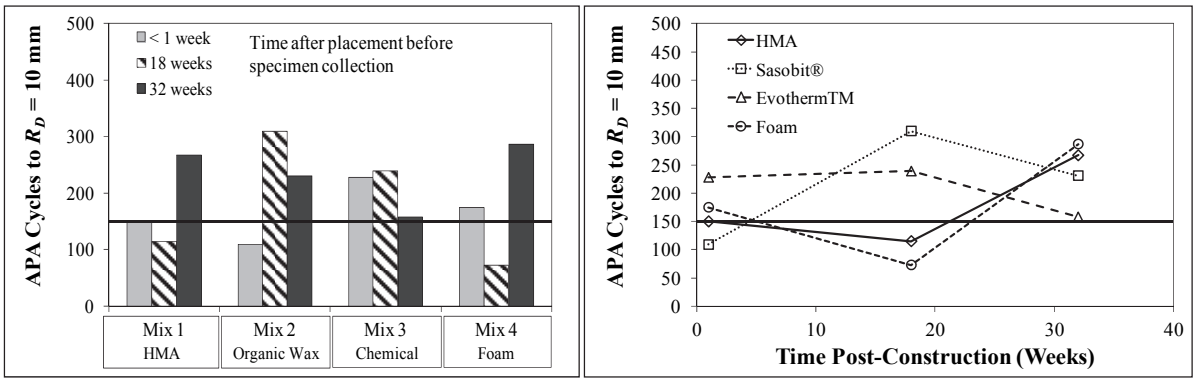
Figure 16. Effect of specimen preparation method on APA LC-1 performance.



As a pavement cures with time after construction, or ages, the binder will gradually stiffen, or harden, resulting in improved resistance to permanent deformation. The rate of this age-hardening behavior of asphalt is influenced by many factors including access to air, temperature, and light (Brown et al., 2009). The temperature of the pavement in the covered test facility is not as high as that of a pavement exposed to full sun and solar radiation. On a typical sunny summer day, the pavement surface temperature in the covered test facility is close to the air temperature (e.g., ~35°C), while the surface temperature of a pavement exposed to the sun outside of the covered test facility is considerably higher (e.g., ~55°C). Therefore a week of curing in the covered test facility would not likely have as much effect on binder stiffness as a week of curing in a fully exposed (i.e., no shade) environment. However, by the conclusion of accelerated traffic testing at 32 weeks after construction, considering the pavement sections to have cured or aged enough in the covered test facility to be comparable to the amount of curing that would occur for a pavement that is exposed to solar radiation in full sun environment after a few weeks of summer temperatures would be reasonable.

Figure 17 presents the LC-1 APA data for PPFC cored specimens by time after placement. Between initial construction and 18 weeks, the APA performance improved as expected for Sasobit®, remained about the same for Evotherm™, and decreased somewhat for HMA and foamed asphalt. Between initial construction and 32 weeks, performance improved as expected for HMA, Sasobit®, and foamed asphalt and decreased somewhat for Evotherm™. When interpreting these mixed results, considering how quickly all of the specimens failed in LC-1 testing at the 64°C binder grade test temperature is important. At these conditions, the specimens failed so quickly that a secondary flow region was not observed in the data; all of the specimens reached 10 mm of rutting within about 300 cycles or fewer. The solid horizontal line on Figure 17 represents the initial performance of the HMA mixture; by 32 weeks after construction, performance of all of the WMAs was at least as good as the initial HMA performance.

Figure 17. Effect of post-construction curing time on APA LC-1 performance.

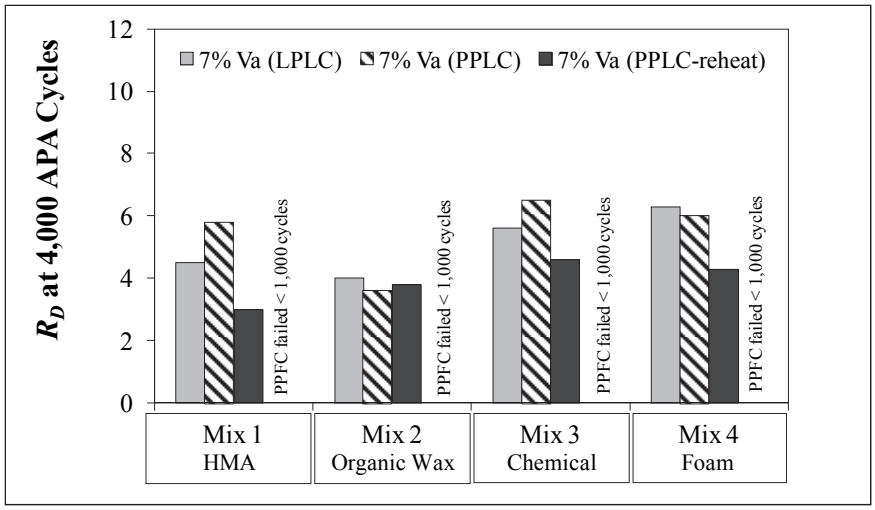


(a) Data by mixture type

(b) Data by cure time

The effect of specimen preparation method on LC-2 APA data tested at 43°C is presented in Figure 18. The performance of PPLC mixture is generally similar to that of LPLC mixture, with a small improvement for HMA and Evotherm™. Interestingly, the performance of reheated PPLC mixture is similar to or not as good as that of PPLC without reheating; this is the opposite of what was observed for the LC-1 test conditions. The reason for this inconsistent result is not clear. Performance of the PPFC mixtures was considerably worse than that of the laboratory-compacted mixtures, a similar result to the other test conditions. Overall, the performance of WMA was generally similar to or better than that of HMA.

Figure 18. Effect of specimen preparation method on APA LC-2 performance.

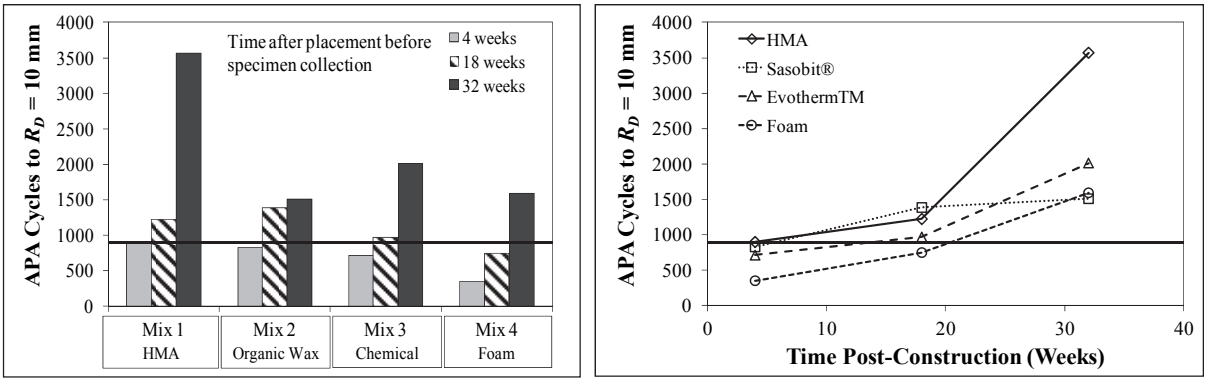


The effect of cure time after construction on PPFC mixture performance is investigated in Figure 19 for LC-2 APA data tested at 43°C. Unlike the LC-1 data discussed previously, an orderly progressive increase in APA performance with time is observed as expected. These specimens did not fail as quickly and secondary flow regions were observed in the data. PPFC specimens at one week or less after construction were not available for LC-2 APA testing; specimens collected 4 weeks after construction were the earliest available. The solid horizontal line on Figure 19 indicates the performance of HMA at 4 weeks post-construction; this is taken to represent the initial performance of the HMA pavement. Initial performance of the WMA at 4 weeks was similar to or somewhat less than the HMA. At 18 weeks after construction, the rutting performance of PPFC mixtures was 1.4 to 2.1 times better than performance of PPFC mixtures 4 weeks after construction. Performance of the WMAs was better than the initial HMA performance for Sasobit® and Evotherm™ and only slightly less for the foamed asphalt. At 32 weeks after construction, rutting performance was 1.8 to 4.6 times better than 4 weeks after construction. Performance of all the WMAs was better than initial performance of the HMA, though less than HMA performance at 32 weeks after construction.

To investigate the effects of test temperature variation on the mixture rutting performance, specimens were tested in the APA for LC-2 at three test temperatures of 37°C, 43°C, and 49°C. The target test temperature during accelerated traffic testing was 43°C, so temperatures 6°C above and below were selected, since it was the same temperature increment of a full PG binder grade change. Figure 20 presents these data for PPLC mixture

that was reheated and compacted to V_a of 5±0.5% to match the average V_a of the full-scale test sections of 5%. The increase in rut depth for a 6°C increase in test temperature is consistently 1.5 to 1.6 times the rut depth at the lower temperature.

Figure 19. Effect of post-construction curing time on APA LC-2 performance.



a) Data by mixture type b) Data by cure time

Figure 20. Effect of test temperature on APA LC-2 performance of PPLC mixture.

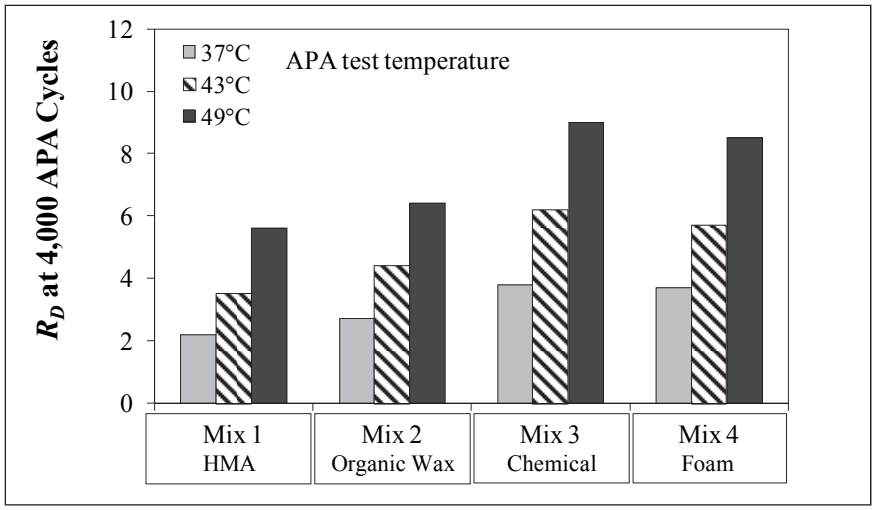
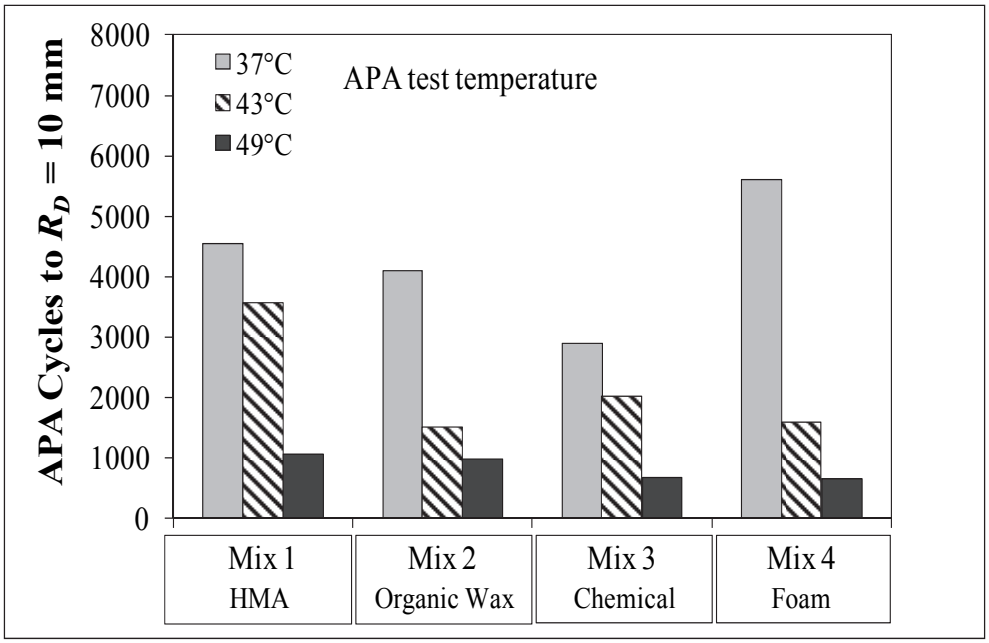


Figure 21 investigates the effect of temperature on LC-2 APA testing of PPFC specimens collected 32 weeks after construction. The change in APA performance for a change in temperature is not as consistent as for the laboratory-compacted specimens. The wider range in V_a for the field-compacted specimens is likely a contributing factor. In general, the increase in APA cycles to 10 mm rut depth for a 6°C decrease in temperature ranged from 1.3 to 3.5.

Figure 21. Effect of test temperature on APA LC-2 performance of PPFC mixture.



4.6 Static load-creep

Table 13 provides the static load-creep test results for Phase 2 PPFC mixtures (reheated before compaction). Values of *m* for all mixtures were well below the maximum recommended value for *m* of 0.45. Values of FT for all mixtures also easily meet the minimum recommended value for FT of 30. Recall that for the LPLC data discussed previously, the HMA barely met suggest criteria while WMAs did not quite meet. Interestingly, the Evotherm™ noticeably outperformed the HMA and other WMAs, although it was the poorest performer in most of the APA data. Based on the APA results, it is possible that reheating of mixture before compaction improved the creep test results to some extent. Static load-creep testing on PPFC specimens was not possible due to the specimen geometry required. Other researchers (Khan et al., 1998) have used creep testing with different geometries to compare permanent deformation characteristics of four mixtures. Cores were taken from the field and plant-produced mixture was re-heated to compact gyratory specimens to the same air void levels. Permanent strain values of the field cores were 1.2 to 1.4 times higher than the gyratory specimens.

Table 13. Phase 2 static load-creep results.

Mixture ID	Replicate	V_a	*a*	*m*	FT	TF
1 (HMA)	1	2.4	0.4915	0.2975	88	217
	2	2.8	0.4881	0.2767	111	271
	Avg.	**2.6**	**0.4898**	**0.2871**	**100**	**244**
2 (Sasobit®)	1	2.8	0.5715	0.2900	78	185
	2	3.1	0.6490	0.3211	50	109
	Avg.	**2.9**	**0.6103**	**0.3056**	**64**	**147**
3 (Evotherm™)	1	1.3	0.7367	0.1488	411	1157
	2	1.3	0.6726	0.1846	240	681
	Avg.	**1.3**	**0.7047**	**0.1667**	**326**	**919**
4 (Foam)	1	2.2	0.5429	0.2578	117	305
	2	2.2	0.4526	0.2962	107	258
	Avg.	**2.2**	**0.4978**	**0.2770**	**112**	**282**

4.7 Repeated load-creep recovery

Table 14 provides the repeated load-creep recovery test results for Phase 2 PPFC mixtures (reheated before compaction). HMA, Evotherm™ and foamed asphalt all met the *m* value requirement of less than 0.45 while Sasobit® only slightly exceeded it. All mixtures exceeded the FN requirement of greater than 200, though Sasobit® was noticeably less than the other mixtures.

Table 14. Phase 2 repeated load-creep recovery results.

Mixture ID	Replicate	V_a	*a*	*m*	FN	TF
1 (HMA)	1	2.4	0.2475	0.3346	671	1773
	2	2.4	0.1511	0.4277	605	1312
	Avg.	**2.4**	**0.1993**	**0.3812**	**638**	**1543**
2 (Sasobit®)	1	2.9	0.1508	0.4563	321	839
	2	2.6	0.1500	0.4577	332	788
	Avg.	**2.8**	**0.1504**	**0.4570**	**327**	**814**
3 (Evotherm™)	1	1.6	0.1838	0.3969	834	1808
	2	1.7	0.1692	0.4169	632	1399
	Avg.	**1.7**	**0.1765**	**0.4069**	**733**	**1604**
4 (Foam)	1	2.2	0.1428	0.3979	862	2056
	2	2.3	0.1411	0.4345	652	1367
	Avg.	**2.2**	**0.1420**	**0.4162**	**757**	**1712**

4.8 Dynamic modulus

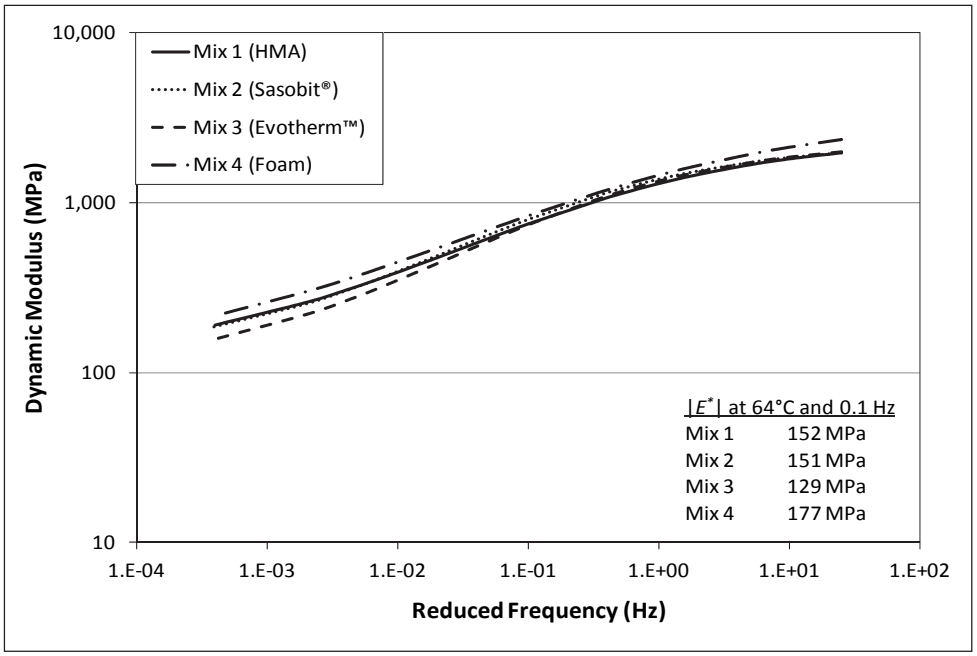
Raw $|E^*|$ test data are located in Table A25 to Table A28 of the appendix. Master curves for each mixture were developed and are shown in Figure A5 through Figure A8 of the appendix. Table 15 summarizes the dynamic modulus master curve fitting parameters for Equation 4 and Equation 5. All four master curves in Table 15 meet or exceed the suggested AASHTO TP 62 criteria for a good quality fit of the data.

Table 15. Phase 2 $|E^*|$ master curve parameters.

Fitting	Mixture Number			
Parameter	1 (HMA)	2 (Sasobit®)	3 (Evotherm™)	4 (Foam)
α	1.3206	1.2672	1.3659	1.4670
β	-1.3309	-1.5715	-1.5236	-1.1269
δ	4.2276	4.2496	4.1660	4.2153
δ	-0.8757	-0.9904	-0.9749	-0.7514
a_1	0.0343	0.0363	0.0379	0.0392
a_2	-9.497E-05	-6.677E-05	-2.860E-05	3.366E-06
S_e / S_y	0.0098	0.0189	0.0251	0.0061
Explained Variance	0.9999	0.9998	0.9996	1.0000

Figure 22 shows all four master curves for the Phase 1 laboratory-produced mixture. In general, the HMA and Sasobit® mixtures have essentially the same stiffnesses for given reduced frequencies. At lower reduced frequencies (i.e., higher temperatures and/or slower loading rates), there are some differences relative to the stiffness of the HMA and Sasobit® mixtures, with the Evotherm™ being less stiff and the foamed asphalt being stiffer. All of the mixtures meet the minimum stiffness criterion recommended by Rushing and Little (2013) to ensure good rutting performance of 124 MPa at 64°C and 0.1 Hz. Overall, the $|E^*|$ data do not suggest that a dramatic reduction in mixture rutting performance should be expected for the WMAs relative to the HMA.

Figure 22. Phase 2 |*E**| master curves.



5 Discussion of Results

5.1 Moisture damage resistance

The moisture damage resistance of WMA was investigated through TSR and Hamburg testing. TSR test results on LPLC specimens indicated increased moisture sensitivity when using WMA processes. Results from PPLC (reheated) specimens indicated wet tensile strength and TSR values for the WMA were similar to those for the HMA. The TSR of all reheated plant-produced mixture greatly exceeded the minimum threshold of 75% in UFGS specifications; no stripping was observed on test specimens.

Hamburg test results on LPLC specimens indicated that the HMA used in this study meets the TxDOT rutting criteria for the Hamburg test, but the rutting performance decreased when the mixture was produced as WMA. Results from plant-produced mixture indicate the reduced aging of the HMA mixture due to the short haul distance considerably affects its performance when compared to the laboratory-produced mixture. However, WMA mixture did not show a significant difference in performance between plant and laboratory-produced specimens. When the PPLC mixtures were reheated, the performance was improved significantly for all mixtures, exceeding the rutting resistance of the LPLC mixtures.

All LPLC data and Hamburg PPLC (reheated) data indicated a potential for increased moisture susceptibility of the WMA mixtures relative to HMA. On the other hand, Hamburg PPLC (no reheating) data, TSR PPLC (reheated) data, and PPFC data indicated similar levels of moisture susceptibility for HMA and WMA. While not investigated in this study due to project resource constraints, the use of an anti-strip additive such as hydrated lime or liquid anti-strip would likely improve the moisture resistance of the WMA mixtures. The potential for reduced moisture resistance of WMA is not considered serious enough to preclude use of WMA for airfield applications, provided that performance testing is included as part of the mixture design process to identify and mitigate any moisture resistance problems before construction of the pavement.

5.2 Rutting performance

APA test results on LPLC material indicate the HMA mixture used in this study may be slightly susceptible to rutting under aircraft loads, as evidenced by high rut depths during APA testing compared to other laboratory mixtures described in literature (Rushing et al. 2012). The rutting performance changed when the mixture was produced as WMA; some WMAs performed better than HMA, while most did not perform as well as HMA. The two APA load conditions provided the same relative rankings of mixtures. LPLC mixture data for static load-creep, repeated load-creep recovery, and dynamic modulus testing indicated a moderate reduction in mixture stiffness for WMA relative to HMA. Overall, LPLC mixture testing indicated a somewhat greater rutting potential for WMA relative to HMA. Generally speaking, the type of WMA technology (i.e., chemical additive, organic wax, or foam) used in the mixture did not correlate with the rut resistance. The change in rutting performance appeared to be related to individual products, highlighting the need for performance tests to approve WMA mixtures prior to field use. Simply prescribing a material class or temperature reduction will not ensure good rutting performance according to these data.

PPLC reheated mixture data for static load-creep, repeated load-creep recovery, and dynamic modulus testing generally indicated similar or somewhat increased mixture stiffness for WMA relative to HMA. PPLC mixture tested in the APA in most cases indicated similar to better performance than HMA, though a in a few instances WMA performance was less than HMA. In general, the PPLC data does not suggest that WMA performance would be dramatically different than HMA performance; this is in contrast to the LPLC data.

In several cases, the performance of PPFC WMA mixture was less than that of HMA. However, performance of all the mixtures improved with cure time after construction and performance of the WMA mixtures ultimately exceeded the initial performance of the HMA. Overall, these data suggest that WMA initially may have a slightly greater propensity for rutting than HMA. The mixture used in this study was intentionally selected to be more rut susceptible than the majority of airfield mixtures. A mixture with a more rut resistant aggregate gradation and/or a polymer-modified binder would be more rut resistant overall and, thus, any initial tenderness from using WMA would be less of a concern. For any WMA mixtures that do exhibit some initial tenderness after construction,

allowing the pavement to cure for a period of time will alleviate the problem. Additionally, use of a rut performance test as part of the mix design process would allow mixtures with poor rutting resistance to be identified prior to construction so that appropriate mix design changes can be made.

5.3 Mixture production and compaction: laboratory vs. field

In general, reheating of PPLC mixture greatly improved performance, and PPLC specimens performed better than field PPFC specimens. For Hamburg testing of WMA mixtures, performance of the LPLC and PPLC without reheating was similar; for HMA mixture on the other hand, performance of the LPLC was considerably better than PPLC without reheating. PPLC mixture tested in the APA indicated similar rut resistance to LPLC when compacted in the laboratory at the design air void content. For APA data, LPLC results generally provided similar relative rankings of mixture performance as PPLC results. Overall, performance results in both rutting and moisture damage performance was improved by reheating of PPLC mixture before compaction.

In general, laboratory-compacted mixtures greatly outperformed field-compacted mixtures. Results from both APA and Hamburg tests indicate the performance of field cores tended to be poor compared to laboratory-compacted specimens. Poor performance of field cores compared to laboratory-compacted specimens has also been documented in literature (Sadasivam 2004; Khan et al. 1998). Other variables that could have affected the performance of the field cores were considered. For example, the fact that the haul from the asphalt plant was relatively short could have affected the asphalt absorption; however, the G_{mm} results from QA testing showed no significant variation between the laboratory-produced and the plant-produced mixes (differences are within single operator precision range). Another possible cause could have been the higher percentage of aggregate passing the 0.075 mm (#200) sieve, which lowers the optimum asphalt content in a mix (Roberts et al. 1996; Brown and Cross 1992); however, differences in binder content between the mixes used in this study were within allowable tolerances.

6 Conclusions and Recommendations

6.1 Conclusions

A pressing need exists for guidance for using WMA on pavement to be trafficked by heavy aircraft. Many of the guidelines for HMA airfield pavement construction are adequate, but the performance of WMA under heavy wheel loads and high tire pressures is unknown. This study investigated changes in binder properties as well as the moisture susceptibility and rutting performance of WMA using TSR, Hamburg, APA, static load-creep, repeated load-creep recovery, and dynamic modulus mixture tests. Based on the results of this study the following conclusions were reached:

- Low PG temperature binder data for some of the WMA additives indicate that performance could potentially be reduced relative to the base binder.
- High PG temperature binder data do not suggest that rutting performance will be detrimentally affected by use WMA additives.
- For this project, the rutting parameter ($G^*/\sin\delta$) and controlling low temperature thermal cracking parameter (BBR m-value) of binder recovered from plant-produced material were reasonably approximated by tests on original binder RTFO residue.
- All WMA laboratory-produced mixtures had lower TSRs than the HMA. All WMA laboratory-produced mixtures had lower Hamburg SIPs than the HMA. Hamburg testing of plant-produced mixture with reheating also indicated lower SIPS for WMA relative to HMA. These tests suggest that WMA mixtures have higher moisture susceptibility than HMA.
- Wet tensile strengths and TSRs of reheated plant-produced WMA were similar to those of plant-produced HMA. Hamburg testing of plant-produced mixture without reheating and of field-compacted mixture indicated similar SIPs for WMA relative to HMA. These data suggest that WMA and HMA have similar levels of moisture susceptibility.
- The overall mixed results for moisture damage testing suggest that WMA may have an increased susceptibility to moisture in some cases. However, adequate performance testing during mixture design and use of anti-strip additives if necessary will likely reduce the risk to acceptable levels.

- Most WMA laboratory-produced mixtures had worse rutting performance than the HMA mixture when tested in the APA, Hamburg, static load-creep, and repeated load-creep recovery tests. Overall, laboratory-produced mixture testing indicated a somewhat reduced mixture stiffness and greater rutting potential for WMA relative to HMA; the category of WMA technology (i.e., chemical additive, organic wax, or foam) was not generally indicative of rut performance.
- Data for plant-produced WMA mixtures, with and without reheating, generally indicated similar mixture stiffness and rutting performance to HMA.
- Initially, the field-compacted WMA mixtures had worse rutting performance than HMA in several cases. However, APA rutting performance of field-compacted mixtures improved with increasing cure time after construction. Rutting performance of the WMA mixtures ultimately surpassed the initial rutting performance of the HMA after a period of curing.
- The overall mixed results from the rut testing suggest that WMA may initially have somewhat greater susceptibility to rutting than comparative HMA due to reduced aging of the binder during production. However, the performance of WMA will match or exceed the initial performance of comparative HMA after a reasonably short curing period.
- In general, both moisture susceptibility and rutting potential test results for plant-produced mixture were improved by reheating.
- All plant-produced mixtures that were compacted in the field had very poor APA and Hamburg rutting performance compared to plant-produced, laboratory-compacted mixture.

6.2 Recommendations

Based on the results of this study, WMA is a viable alternative to HMA for wearing surfaces on airfields. This recommendation is limited to laboratory performance test data. The sharp reduction in rutting performance of field cores compared to laboratory-compacted specimens was comparable for HMA and WMA, indicating it is a function of the field-compacted asphalt concrete properties and not specifically attributable to WMA. Specific recommendations for future work include the following:

- Accelerated traffic testing of the test sections from which core specimens were produced will serve to validate the rutting performance of WMA relative to HMA.

- Performance test protocols need to be established for field-compacted specimens to ensure quality assurance testing accurately reflects in-service pavement conditions.
- The use of anti-strip agents in conjunction with WMA should be investigated to see if moisture susceptibility is a real concern and, if so, how it can best be mitigated.
- A long-term performance test section should be constructed on an active airfield. Both HMA and WMA mixtures utilizing the same source materials should be placed and their performance be monitored.
- The performance of WMA in terms of environmental cracking and long-term durability should be investigated to quantify possible long-term benefits relative to HMA such as potentially reduced maintenance requirements.

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Appendix A: Test Data

Table A1. Extracted aggregate test results for plant-produced mixtures 1 and 2.

Aggregate Property	JMF Target	Mixture 1				Mixture 2			
		Rep 1[a]	Rep 2[a]	Rep 3[b]	Avg.	Rep 1[a]	Rep 2[a]	Rep 3[b]	Avg.
- 25.0 mm	100	100	100	100	100	100	100	100	100
- 19.0 mm	100	100	100	100	100	100	100	100	100
- 12.5 mm	96 ± 8	98	96	97	97	95	96	96	96
- 9.5 mm	85 ± 8	92	90	88	90	88	88	88	88
- 4.75 mm	68 ± 8	74	70	71	72	69	70	68	69
- 2.36 mm	54 ± 6	56	53	52	54	52	52	50	52
- 1.18 mm	38 ± 6	---	---	37	37	---	---	35	35
- 0.60 mm	28 ± 6	28	27	27	27	27	26	26	26
- 0.30 mm	15 ± 6	16	15	15	15	15	15	14	15
- 0.15 mm	7 ± 2	---	---	8	8	---	---	7	7
- 0.075 mm	4.9 ± 2	6.0	6.0	5.6	5.9	5.4	5.6	5.5	5.5
G_{sb}	2.609	---	---	2.608	2.608	---	---	2.616	2.616
G_{sa}	2.688	---	---	2.665	2.665	---	---	2.670	2.670
Abs (%)	1.15	---	---	0.81	0.81	---	---	0.78	0.78

a) Replicates 1 and 2 are Quality Control (QC) data tested and provided by the asphalt producer.

b) Replicate 3 is Quality Assurance (QA) data tested by the research team.

Table A2. Extracted aggregate test results for plant-produced mixtures 3 and 4.

Aggregate Property	JMF Target	Mixture 3				Mixture 4			
		Rep 1[a]	Rep 2[a]	Rep 3[b]	Avg.	Rep 1[a]	Rep 2[a]	Rep 3[b]	Avg.
- 25.0 mm	100	100	100	100	100	100	100	100	100
- 19.0 mm	100	100	100	100	100	100	100	100	100
- 12.5 mm	96 ± 8	96	96	96	96	96	96	97	97
- 9.5 mm	85 ± 8	86	84	89	86	89	89	89	89
- 4.75 mm	68 ± 8	66	66	70	67	70	70	71	71
- 2.36 mm	54 ± 6	51	52	52	51	54	54	53	53
- 1.18 mm	38 ± 6	---	---	38	38	---	---	38	38
- 0.60 mm	28 ± 6	27	27	28	27	28	28	28	28
- 0.30 mm	15 ± 6	16	16	16	16	15	15	16	15
- 0.15 mm	7 ± 2	---	---	9	9	---	---	8	8
- 0.075 mm	4.9 ± 2	6.2	5.9	7.2	6.4	6.2	6.2	6.5	6.3
G_{sb}	2.609	---	---	2.603	2.603	---	---	2.608	2.608
G_{sa}	2.688	---	---	2.669	2.669	---	---	2.662	2.662
Abs (%)	1.15	---	---	0.95	0.95	---	---	0.78	0.78

a) Replicates 1 and 2 are Quality Control (QC) data provided by the asphalt producer.

b) Replicate 3 is Quality Assurance (QA) data tested by the research team.

Table A3. Theoretical maximum specific gravity results for laboratory-produced mixtures.

Mix ID	P_b	Rep	G_{mm}
1	5.3	1	2.455
		2	2.466
		Avg.	**2.461**
2	5.2	1	2.459
		2	2.466
		Avg.	**2.463**
3	5.2	1	2.462
		2	2.463
		Avg.	**2.463**
4	5.1	1	2.466
		2	2.467
		Avg.	**2.467**
4a	5.2	1	2.459
		2	2.459
		Avg.	**2.459**
5	5.2	1	2.458
		2	2.458
		Avg.	**2.458**
6	5.2	1	2.456
		2	2.463
		Avg.	**2.460**
7	5.1	1	2.459
		2	2.456
		Avg.	**2.458**
8	5.2	1	2.459
		2	2.459
		Avg.	**2.459**
9	5.2	1	2.457
		2	2.461
		Avg.	**2.459**
10	5.2	1	2.459
		2	2.461
		Avg.	**2.460**
11	5.1	1	2.460
		2	2.459
		Avg.	**2.460**
12	5.1	1	2.455
		2	2.458
		Avg.	**2.457**

Table A4. Bulk specific gravity results for all laboratory-produced mixtures.

Mix ID	P_b	G_{mm}	Replicate	T 166		T 331	
				G_{mb}	V_a (%)	G_{mb}	V_a (%)
1	5.3	2.461	1	2.359	4.1	2.352	4.4
			2	2.365	3.9	2.359	4.1
			Avg.	**2.362**	**4.0**	**2.356**	**4.3**
2	5.2	2.463	1	2.365	4.0	2.365	4.0
			2	2.368	3.9	2.349	4.6
			Avg.	**2.367**	**3.9**	**2.357**	**4.3**
3	5.2	2.463	1	2.373	3.7	2.368	3.9
			2	2.362	4.1	2.361	4.1
			Avg.	**2.368**	**3.9**	**2.365**	**4.0**
4	5.1	2.467	1	2.371	3.9	2.364	4.2
			2	2.366	4.1	2.358	4.4
			Avg.	**2.369**	**4.0**	**2.361**	**4.3**
4a	5.2	2.459	1	2.372	3.5	2.365	3.8
			2	2.378	3.3	2.378	3.3
			Avg.	**2.375**	**3.4**	**2.372**	**3.6**
5	5.2	2.458	1	2.353	4.3	2.355	4.2
			2	2.368	3.7	2.368	3.7
			Avg.	**2.361**	**4.0**	**2.362**	**3.9**
6	5.2	2.460	1	2.356	4.2	2.355	4.3
			2	2.366	3.8	2.366	3.8
			Avg.	**2.361**	**4.0**	**2.361**	**4.0**
7	5.1	2.458	1	2.364	3.8	2.365	3.8
			2	2.365	3.8	2.366	3.7
			Avg.	**2.365**	**3.8**	**2.366**	**3.8**
8	5.2	2.459	1	2.365	3.8	2.365	3.8
			2	2.365	3.8	2.360	4.0
			Avg.	**2.365**	**3.8**	**2.363**	**3.9**
9	5.2	2.459	1	2.366	3.8	2.364	3.9
			2	2.372	3.5	2.372	3.5
			Avg.	**2.369**	**3.7**	**2.368**	**3.7**
10	5.2	2.460	1	2.369	3.7	2.368	3.7
			2	2.375	3.5	2.377	3.4
			Avg.	**2.372**	**3.6**	**2.373**	**3.6**
11	5.1	2.460	1	2.361	4.0	2.361	4.0
			2	2.369	3.7	2.367	3.8
			Avg.	**2.365**	**3.9**	**2.364**	**3.9**
12	5.1	2.457	1	2.367	3.7	2.371	3.5
			2	2.366	3.7	2.368	3.6
			Avg.	**2.367**	**3.7**	**2.370**	**3.6**

Table A5. QC and QA results for all plant-produced mixtures.

Mix ID	Rep	P_b	G_{mm}	T 166		T 331	
				G_{mb}	V_a (%)	G_{mb}	V_a (%)
1-QC[a]	1	5.33	2.443	2.385	2.4	---	---
	2	5.20	2.444	2.384	2.5	---	---
	3	---	---	2.391	2.2	---	---
	4	---	---	2.393	2.1	---	---
	Avg.	**5.27**	**2.444**	**2.388**	**2.3**	**—**	**—**
1-QA[b]	1	5.37	2.452	2.397	2.3	2.398	2.3
	2	5.19	2.456	2.400	2.2	2.390	2.6
	Avg.	**5.28**	**2.454**	**2.398**	**2.3**	**2.394**	**2.4**
2-QC[a]	1	5.27	2.443	2.399	1.8	---	---
	2	5.24	2.441	2.398	1.8	---	---
	3	---	---	2.380	2.5	---	---
	4	---	---	2.378	2.6	---	---
	Avg.	**5.26**	**2.442**	**2.389**	**2.2**	**—**	**—**
2-QA[b]	1	4.91	2.461	2.383	3.1	2.379	3.3
	2	4.90	2.459	2.385	3.0	2.379	3.3
	Avg.	**4.91**	**2.460**	**2.384**	**3.1**	**2.379**	**3.3**
3-QC[a]	1	4.96	2.457	2.417	1.6	---	---
	2	5.11	2.454	2.424	1.3	---	---
	3	---	---	2.407	2.0	---	---
	4	---	---	2.405	2.1	---	---
	Avg.	**5.04**	**2.456**	**2.413**	**1.7**	**—**	**—**
3-QA[b]	1	4.80	2.462	2.410	2.2	2.408	2.2
	2	4.96	2.463	2.418	1.8	2.409	2.2
	Avg.	**4.88**	**2.463**	**2.414**	**2.0**	**2.409**	**2.2**
4-QC[a]	1	4.98	2.449	2.389	2.4	---	---
	2	4.94	2.447	2.403	1.8	---	---
	3	---	---	2.403	1.8	---	---
	4	---	---	2.411	1.5	---	---
	Avg.	**4.96**	**2.448**	**2.402**	**1.9**	**—**	**—**
4-QA[b]	1	4.86	2.471	2.369	4.1	2.349	4.9
	2	4.81	2.470	2.343	5.2	2.398	2.9
	Avg.	**4.84**	**2.471**	**2.356**	**4.7**	**2.374**	**3.9**

a) Quality Control (QC) results tested and provided by the asphalt producer. Asphalt contents were determined by nuclear method (AASHTO T 287).

b) Quality Assurance (QA) results tested by the research team. Asphalt contents were determined by trichloroethylene solvent extraction (AASHTO T 164 Method A).

Table A6. Phase 1 binder test data.

	Original Binder			RTFO Residue T 240			PAV Residue R 28[e]				
	T 316[a]	T 315[b]		T240[c]	T 315[d]		T 315[f]		T 313[g]		
ID	(Pa•s)	(°C)	(kPa)	(%)	(°C)	(kPa)	(°C)	(kPa)	(°C)	(MPa)	(—)
1	0.453	64	1.60	-0.108	64	3.68	22	6930	-12	233	0.319
		70	0.766		70	1.68	25	4640	-18	382	0.259
2	0.400	64	3.23	-0.088	70	2.62	25	5600	-6	189	0.310
		70	1.51		76	1.22	28	3900	-12	215	0.284
		76	0.748		---	---	---	---	---	---	---
3	0.433	64	1.70	-0.250	64	3.56	22	7100	-12	219	0.310
		70	0.811		70	1.63	25	4800	-18	442	0.239
5	0.425	64	1.43	-0.117	64	3.15	22	7290	-6	195	0.306
		70	0.689		70	1.46	25	4930	-12	202	0.292
6	0.360	70	1.52	-0.212	70	2.39	25	5800	-12	256	0.321
		76	0.780		76	1.19	28	4000	-18	465	0.232
7	0.450	64	1.58	-0.058	64	2.75	25	5080	-6	187	0.301
		70	0.760		70	1.27	25	3470	-12	200	0.281
8	0.393	70	1.14	-0.185	64	4.12	22	7240	-12	207	0.343
		76	0.563		70	1.94	25	4830	-18	449	0.247
9	0.450	64	1.44	-0.157	64	3.58	25	5050	-6	190	0.307
		70	0.691		70	1.64	28	3460	-12	212	0.280
10	0.345	70	2.75	-0.121	76	3.71	25	5890	-6	186	0.311
		76	1.64		82	2.37	28	4090	-12	217	0.279
		82	0.989		88	1.49	–	---	---	---	---
11	0.423	64	1.38	-0.212	64	3.29	22	7220	-12	232	0.322
		70	0.667		70	1.48	25	4890	-18	383	0.262

a) Test performed at 135°C; criteria is maximum 3 Pa•s.

b) Test performed at 10 rad/s and data is for G*/sin δ; criteria is minimum 1.00 kPa.

c) Test performed at 163°C for 85 minutes; criteria is 0±1.00%.

d) Test performed at 10 rad/s and data is for G*/sin δ; criteria is minimum 2.20 kPa.

e) Conditioning performed at 100°C and 2.1 MPa for 20 hours.

f) Test performed at 10 rad/s and data is for G*sin δ; criteria is maximum 5000 kPa.

g) Data reported at 60 seconds; criteria are maximum 300 MPa and minimum 0.300.

Table A7. TSR data for laboratory-produced mixtures 1 to 6.

Mix ID	P_b	Rep	Un-Conditioned Set		Conditioned Set				TSR (%)
			V_a (%)	S_t (kPa)	V_a (%)	Sat-1 (%)[a]	Sat-2 (%)[b]	S_t (kPa)	
1	5.3	1	6.4	2610	6.5	79.3	84.1	2195	---
		2	6.3	2725	6.3	60.2	64.7	2290	---
		3	6.2	2590	6.4	55.9	58.8	2230	---
		Avg.	6.3	2642	6.4	65.1	69.2	2238	84.7
2	5.2	1	6.4	2360	6.1	67.3	72.1	1590	---
		2	6.4	2295	6.5	60.2	65.7	1795	---
		3	6.5	2350	6.7	64.4	69.4	1690	---
		Avg.	6.4	2335	6.4	64.0	69.1	1692	72.4
3	5.2	1	6.8	1990	7.0	67.6	68.5	1460	---
		2	6.9	2000	6.8	61.5	65.8	1540	---
		3	7.0	1900	7.0	67.4	71.6	1490	---
		Avg.	6.9	1963	6.9	65.5	68.6	1497	76.2
4	5.1	1	7.0	2490	6.8	59.4	66.8	1620	---
		2	6.8	2395	7.1	63.7	66.3	1570	---
		3	6.9	2490	6.9	57.8	59.9	1920	---
		Avg.	6.9	2458	6.9	60.3	64.3	1703	69.3
4a	5.2	1	6.1	2190	6.4	66.9	85.7	1175	---
		2	6.4	2125	6.4	66.6	83.5	1125	---
		3	6.3	2095	6.1	62.7	82.2	1225	---
		Avg.	6.3	2137	6.3	65.4	83.8	1175	55.0
5	5.2	1	6.5	2190	6.5	55.7	74.4	1475	---
		2	6.4	2210	6.7	66.0	83.4	1125	---
		3	6.4	2105	6.0	59.2	75.9	1250	---
		Avg.	6.4	2168	6.4	60.3	77.9	1283	59.2
6	5.2	1	6.0	2210	6.6	63.2	79.3	1195	---
		2	6.2	2195	6.1	60.5	79.2	1305	---
		3	6.4	2400	6.1	59.9	78.0	1405	---
		Avg.	6.2	2268	6.3	61.2	78.8	1302	57.4

a) Sat-1 is the degree of saturation after partial vacuum saturation.

b) Sat-2 is the degree of saturation after partial vacuum saturation and moisture conditioning.

Table A8. TSR data for laboratory-produced mixtures 7 to 12.

Mix ID	P_b	Rep	Un-Conditioned Set		Conditioned Set				TSR (%)
			V_a (%)	S_t (kPa)	V_a (%)	Sat-1 (%)[a]	Sat-2 (%)[b]	S_t (kPa)	
7	5.1	1	6.9	2475	6.8	64.6	81.5	1105	---
		2	6.6	2495	7.1	68.7	90.3	960	---
		3	7.0	2590	6.7	72.5	91.4	920	---
		Avg.	6.8	2520	6.8	68.6	87.7	995	39.5
8	5.2	1	6.7	2390	6.7	67.4	79.3	1175	---
		2	6.8	2405	6.5	67.6	82.0	1210	---
		3	6.7	2375	6.7	69.7	84.5	1200	---
		Avg.	6.7	2390	6.6	68.2	81.9	1195	50.0
9	5.2	1	6.7	2290	6.6	56.1	76.6	1175	---
		2	6.7	2180	7.1	62.4	80.1	1090	---
		3	6.5	2225	6.4	61.3	82.8	1105	---
		Avg.	6.6	2232	6.7	59.9	79.8	1123	50.3
10	5.2	1	7.0	2150	7.4	71.8	83.1	1300	---
		2	6.8	2110	7.1	65.6	78.3	1390	---
		3	7.0	2000	6.7	64.2	77.3	1525	---
		Avg.	6.9	2087	7.0	67.2	79.6	1405	67.3
11	5.1	1	6.6	2050	6.9	65.6	81.9	1225	---
		2	6.9	1960	6.6	72.2	85.5	1110	---
		3	6.9	2090	6.8	66.5	82.5	1100	---
		Avg.	6.8	2033	6.8	68.1	83.3	1145	56.3
12	5.1	1	6.8	1900	6.5	61.2	81.8	990	---
		2	6.5	1905	6.5	63.1	87.3	900	---
		3	6.7	1995	7.0	67.8	88.5	925	---
		Avg.	6.7	1933	6.7	64.1	85.9	938	48.5

a) Sat-1 is the degree of saturation after partial vacuum saturation.

b) Sat-2 is the degree of saturation after partial vacuum saturation and moisture conditioning.

Table A9. Hamburg data for all laboratory-produced mixtures.

Mix ID	V_a (%)	SIP	$P_{12.5}$	Rut Depth by Pass Level (mm)				Linear Creep[a]		Linear Stripping[b]	
				5k pass	10k pass	15k pass	20k pass	Slope	Intercept	Slope	Intercept
1	7.2	9700	12450	5.7	8.2	---[c]	---[c]	380	3.8	1533	-7.5
2	7.1	4200	5500	10.3	---[c]	---[c]	---[c]	964	3.5	3829	-9.3
3	6.9	2650	3700	---[c]	---[c]	---[c]	---[c]	1827	3.8	3540	-0.8
4	7.1	4300	5450	10.4	---[c]	---[c]	---[c]	1156	2.6	4319	-10.4
4a	7.0	3300	4300	---[c]	---[c]	---[c]	---[c]	1886	2.5	4420	-6.4
5	6.6	2500	3350	---[c]	---[c]	---[c]	---[c]	1949	2.8	5614	-6.3
6	6.6	3800	4463	---[c]	---[c]	---[c]	---[c]	1188	2.8	4736	-10.6
7	6.9	3500	5000	12.5	---[c]	---[c]	---[c]	1357	3.1	3138	-3.1
8	7.0	5600	5478	6.3	---[c]	---[c]	---[c]	824	3.5	3957	-15.0
9	6.8	2450	3700	---[c]	---[c]	---[c]	---[c]	1644	2.8	4702	-4.8
10	6.6	5000	5200	9.2	---[c]	---[c]	---[c]	876	3.7	3077	-6.6
11	7.5	3300	4250	13.2	---[c]	---[c]	---[c]	1648	4.1	4147	-3.6
12	7.1	2550	3350	---[c]	---[c]	---[c]	---[c]	1771	3.2	5959	-7.5

a) Slope (10^{-6} pass per 1-mm rut) and intercept (mm) parameters for fit of line to the linear creep region.

b) Slope (10^{-6} pass per 1-mm rut) and intercept (mm) parameters for fit of line to the linear stripping region.

c) Specimens reached termination rut depth before reaching this pass level.

Table A10. APA data for all laboratory-produced mixtures.

Mixture ID	LC-1 tested at 64°C					LC-2 tested at 43°C				
	V_a (%)	Cycles to R_D = 10 mm	a^a	b^a	R^{2a}	V_a (%)	R_D at 4k Cycles	a^a	b^a	R^{2a}
1	4.3	3830	0.1475	0.5111	0.98	6.8	4.5	0.0482	0.5485	0.99
2	4.3	4915	0.1339	0.5055	0.99	6.9	4.0	0.0486	0.5326	0.99
3	4.0	2352	0.0231	0.7815	0.99	6.6	5.6	0.0378	0.6082	0.98
4	4.3	2517	0.0738	0.6292	0.99	7.1	6.3	0.0687	0.5464	0.99
4a	3.6	2792	0.1411	0.5369	0.99	---	---	---	---	---
5	4.0	2111	0.0393	0.7253	0.99	---	---	---	---	---
6	4.1	2330	0.0870	0.6155	0.99	---	---	---	---	---
7	3.8	2075	0.0488	0.6938	0.99	---	---	---	---	---
8	3.9	1723	0.0126	0.8937	0.99	---	---	---	---	---
9	3.7	1487	0.0700	0.6777	0.99	---	---	---	---	---
10	3.6	4432	0.0746	0.5757	0.97	---	---	---	---	---
11	3.9	1343	0.0217	0.8512	0.99	---	---	---	---	---
12	3.6	1340	0.0486	0.7384	0.99	---	---	---	---	---

a) The regression constants *a* and *b* and the R^2 values refer to Equation 1.

Table A11. |*E**| data for laboratory-produced mixture 1.

Test Temperature	Test Frequency	Replicate 1		Replicate 2		Replicate 3		Average	
		|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*
(°C)	(Hz)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)
21	25	1691	6.0	1656	5.9	1595	6.5	1647	6
	10	1380	9.8	1401	8.6	1489	11.0	1423	10
	5	1435	9.4	1353	11.5	1477	12.1	1422	11
	1	1058	11.9	963	17.9	1016	17.1	1012	16
	0.5	832	15.0	752	17.0	793	18.1	792	17
	0.1	701	19.0	569	21.8	598	21.4	623	21
37	25	1512	14.1	1451	18.8	1527	21.9	1497	18
	10	1239	23.2	1096	21.8	1114	23.1	1150	23
	5	1041	16.7	942	21.7	1009	26.0	997	21
	1	633	23.4	561	23.3	614	29.2	603	25
	0.5	457	23.1	410	23.6	428	26.1	432	24
	0.1	325	22.8	287	21.4	293	25.4	302	23
54	25	873	23.7	701	17.8	597	12.9	724	18
	10	633	20.4	556	19.3	482	20.4	557	20
	5	498	18.7	451	19.7	415	16.6	455	18
	1	306	19.4	280	20.7	264	16.8	283	19
	0.5	230	19.1	210	21.7	192	18.3	211	20
	0.1	175	16.2	157	20.4	137	18.7	156	18
Specimen Air Voids (%)		4.0		4.0		4.3		4.1	

Table A12. |*E**| data for laboratory-produced mixture 2.

Test Temperature	Test Frequency	Replicate 1		Replicate 2		Replicate 3		Average	
		|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*
(°C)	(Hz)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)
21	25	1689	3.4	1643	8.1	1523	4.8	1618	5
	10	1439	7.0	1367	9.6	1514	7.4	1440	8
	5	1450	9.5	1334	11.3	1370	13.4	1385	11
	1	1046	14.4	969	17.0	1036	15.7	1017	16
	0.5	730	15.7	778	19.3	807	19.8	772	18
	0.1	603	17.7	593	21.0	623	20.4	606	20
37	25	1759	14.4	1658	10.2	1339	14.5	1585	13
	10	1190	13.8	1229	21.4	1089	19.6	1169	18
	5	1030	18.8	1065	21.4	1001	21.2	1032	20
	1	634	20.7	633	25.4	596	20.6	621	22
	0.5	439	23.4	465	25.2	431	23.0	445	24
	0.1	312	21.5	320	22.3	301	21.1	311	22
54	25	770	21.4	682	20.0	729	23.8	727	22
	10	612	16.5	578	19.1	631	14.5	607	17
	5	464	17.8	489	18.3	475	17.4	476	18
	1	330	16.7	318	17.3	296	23.2	315	14
	0.5	226	18.9	232	19.3	224	19.7	227	18
	0.1	169	18.4	179	17.4	162	18.6	170	18
Specimen Air Voids (%)		3.9		3.9		4.2		4.0	

Table A13. |*E**| data for laboratory-produced mixture 3.

Test Temperature	Test Frequency	Replicate 1		Replicate 2		Replicate 3		Average	
		|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*
(°C)	(Hz)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)
21	25	2239	8.9	1978	1.9	1582	9.2	1933	7
	10	1793	7.5	1575	8.5	1543	10.6	1637	9
	5	1783	11.0	1491	12.0	1506	12.1	1593	12
	1	1339	17.3	1134	17.5	1035	17.5	1169	17
	0.5	1022	19.3	814	18.2	782	15.8	873	18
	0.1	733	22.1	623	23.9	570	24.1	642	23
37	25	1359	12.0	1556	18.0	1290	25.8	1402	19
	10	1044	20.5	992	18.9	1075	23.3	1037	21
	5	983	21.6	922	20.0	894	23.9	933	22
	1	559	24.1	527	23.9	552	23.6	546	24
	0.5	397	25.4	378	22.8	377	23.6	384	24
	0.1	274	21.8	268	20.3	273	21.6	272	21
54	25	717	19.4	716	22.1	775	19.8	736	20
	10	525	20.3	521	18.2	548	18.2	531	19
	5	417	17.7	429	16.1	427	16.2	424	17
	1	292	13.1	282	15.9	245	16.6	273	15
	0.5	187	18.1	207	19.3	203	19.9	199	18
	0.1	133	18.8	150	18.2	149	18.0	144	18
Specimen Air Voids (%)		4.2		4.1		4.3		4.2	

Table A14. |*E**| data for laboratory-produced mixture 4.

Test Temperature	Test Frequency	Replicate 1		Replicate 2		Replicate 3		Average	
		|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*
(°C)	(Hz)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)
21	25	1333	8.4	1599	10.4	1636	10.8	1523	10
	10	1199	10.1	1525	11.1	1498	11.1	1407	11
	5	1175	13.9	1379	17.3	1489	12.8	1348	15
	1	867	19.6	997	15.2	1002	18.6	955	18
	0.5	683	22.2	743	16.5	775	19.8	734	20
	0.1	470	23.4	566	20.9	560	24.6	532	23
37	25	1301	22.8	1552	17.4	1162	20.3	1338	20
	10	943	17.9	1079	16.6	977	18.8	1000	18
	5	794	19.5	922	21.2	819	22.5	845	21
	1	464	23.5	571	22.6	478	21.4	504	23
	0.5	337	24.4	411	26.1	341	23.3	363	25
	0.1	247	21.3	284	21.3	255	19.7	262	21
54	25	558	20.9	743	19.3	584	14.6	628	18
	10	484	19.8	585	22.6	516	21.1	528	21
	5	383	17.9	523	22.0	432	18.2	446	19
	1	248	25.1	314	61.2	279	17.6	280	16
	0.5	174	21.8	236	25.0	199	18.8	203	14
	0.1	115	21.3	174	19.6	141	18.8	143	20
Specimen Air Voids (%)		4.2		3.6		4.1		4.0	

Figure A1. |*E**| master curve for laboratory-produced mixture 1.

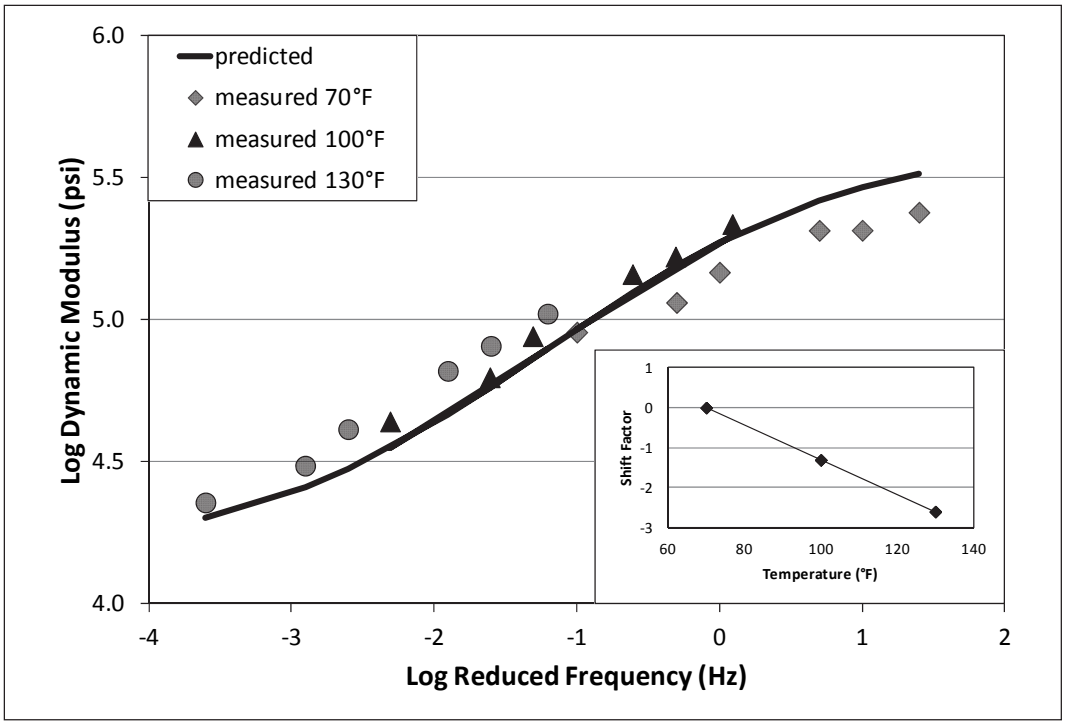


Figure A2. |*E**| master curve for laboratory-produced mixture 2.

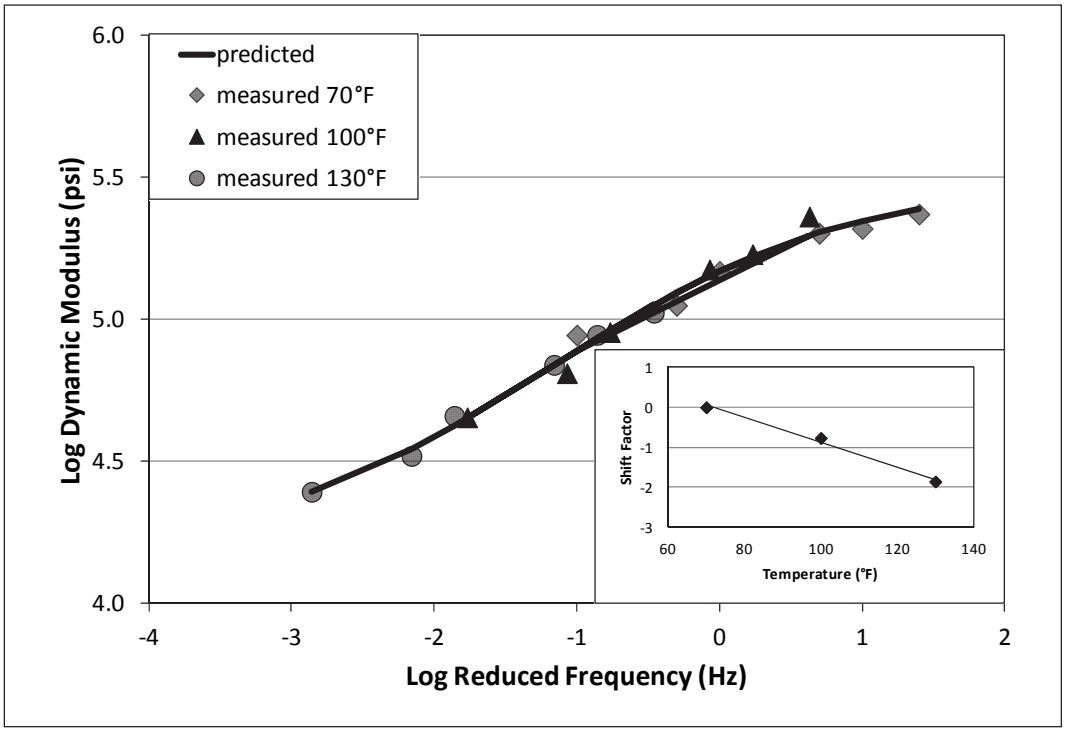


Figure A3. |E*| master curve for laboratory-produced mixture 3.

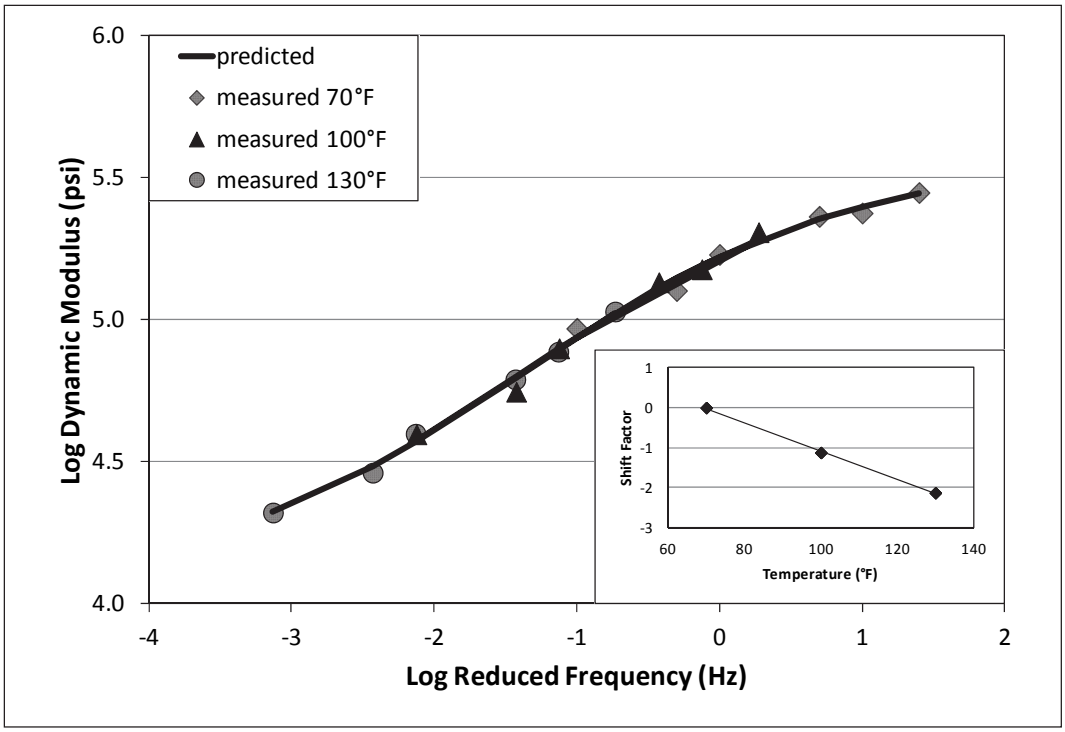


Figure A4. |*E**| master curve for laboratory-produced mixture 4.

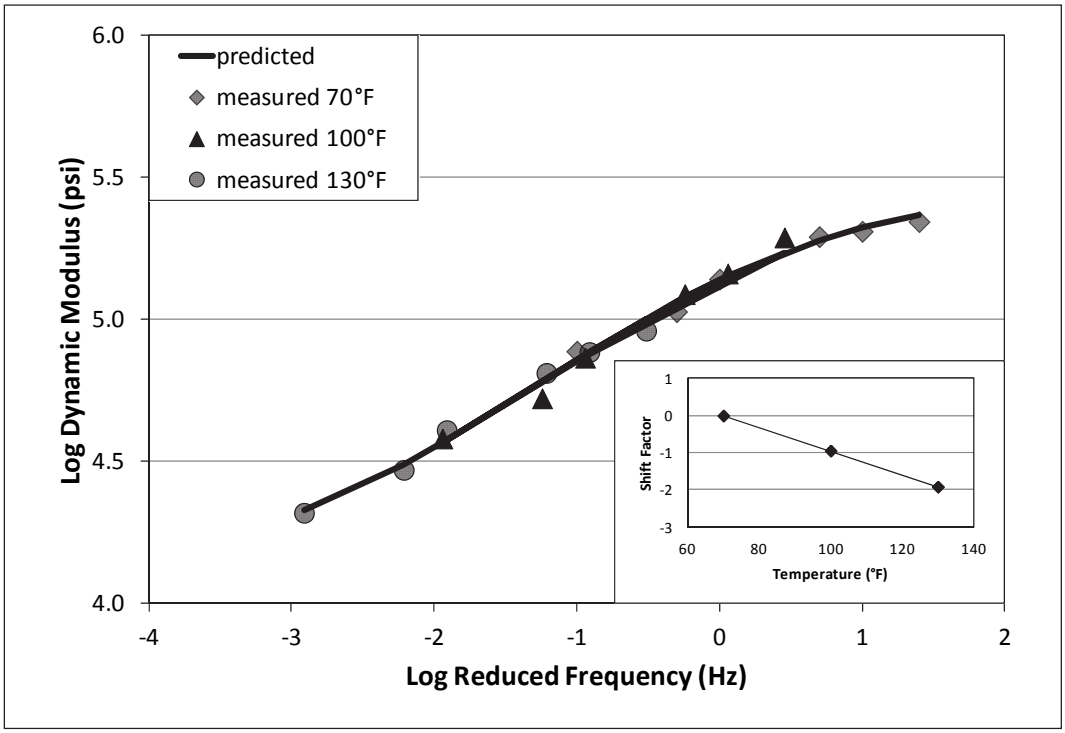


Table A15. Recovered binder test data.

	Recovered Binder			PAV Residue R 28[c]				
	T 316[a]	T 315[b]		T 315[d]		T 313[e]		
ID	(Pa•s)	(°C)	(kPa)	(°C)	(kPa)	(°C)	(MPa)	(—)
1	0.690	70	2.24	25	3600	-12	147	0.324
		76	1.07	22	5200	-18	280	0.278
2	0.700	70	2.85	25	4230	-6	89	0.344
		76	1.28	22	6020	-12	184	0.288
3	0.785	64	3.26	25	3500	-12	150	0.338
		70	1.51	22	5180	-18	298	0.285
4	1.250	70	2.90	25	3820	-6	69.9	0.371
		76	1.35	22	5450	-12	149	0.317
		---	---	---	---	-18	304	0.260

a) Test performed at 135°C.

b) Test performed at 10 rad/s and data is for G*/sin δ; criteria is minimum 2.20 kPa.

c) Conditioning performed at 100°C and 2.1 MPa for 20 hours.

d) Test performed at 10 rad/s and data is for G*sin δ; criteria is maximum 5000 kPa.

e) Data reported at 60 seconds; criteria are maximum 300 MPa and minimum 0.300.

Table A16. Theoretical maximum specific gravity test results at varying times.

Mix ID	Time after production (min)	Rep 1	Rep 1	Difference	Average
1 (HMA)	25	2.455	2.459	0.005	2.457
	65	2.462	2.457	0.004	2.460
	125	2.457	2.459	0.002	2.458
	180	2.464	2.458	0.006	2.461
	240	2.464	2.463	0.001	2.464
	reheat	2.464	2.463	0.001	2.464
2 (Sasobit®)	30	---[a]	---[a]	---[a]	---[a]
	60	2.463	---[a]	---[a]	2.463
	125	2.458	---[a]	---[a]	2.458
	180	2.460	---[a]	---[a]	2.460
	240	2.464	2.469	0.005	2.467
	reheat	2.467	2.468	0.001	2.467
3 (Evotherm™)	20	2.463	2.467	0.004	2.465
	80	2.466	2.468	0.003	2.467
	120	2.468	2.472	0.004	2.470
	195	2.469	2.469	0.000	2.469
	240	2.471	2.470	0.001	2.471
	reheat	2.459	2.460	0.001	2.459
4 (Foam)	15	2.468	2.461	0.007	2.465
	65	2.466	2.469	0.003	2.467
	130	2.461	2.464	0.003	2.462
	185	2.472	2.465	0.007	2.469
	245	2.470	2.469	0.001	2.469
	reheat	2.462	2.459	0.003	2.460

a) Data not available due to laboratory testing error.

Table A17. TSR data for all plant-produced mixtures.

Mix ID	P_b	Rep	Un-Conditioned Set		Conditioned Set				TSR (%)
			V_a (%)	S_t (kPa)	V_a (%)	Sat-1 (%)[a]	Sat-2 (%)[b]	S_t (kPa)	
1	5.3	1	6.7	2060	6.7	63.3	73.5	2005	---
		2	6.9	2125	6.5	60.3	77.8	2180	---
		3	6.7	2200	6.8	65.2	72.9	2060	---
		Avg.	6.8	2128	6.7	62.9	74.7	2082	97.8
2	5.1	1	6.6	2225	6.5	60.1	74.0	2025	---
		2	6.5	2092	6.8	59.2	71.9	2100	---
		3	6.8	2090	6.6	66.3	78.0	2110	---
		Avg.	6.6	2136	6.6	61.9	74.6	2078	97.3
3	5.0	1	6.0	2185	6.4	67.4	84.4	2220	---
		2	6.4	2125	6.2	62.9	80.4	2290	---
		3	6.2	2175	6.0	65.9	90.2	2110	---
		Avg.	6.2	2162	6.2	65.4	84.0	2207	102.1
4	4.9	1	6.1	2400	6.4	66.0	80.8	2410	---
		2	6.7	2160	6.1	69.0	85.4	2410	---
		3	6.0	2470	6.3	64.7	75.6	2290	---
		Avg.	6.3	2343	6.2	66.6	80.6	2370	101.1

a) Sat-1 is the degree of saturation after partial vacuum saturation.

b) Sat-2 is the degree of saturation after partial vacuum saturation and moisture conditioning.

Table A18. Hamburg data for all PPLC mixtures produced without reheating.

Mix ID	V_a (%)	SIP	$P_{12.5}$	Rut Depth by Pass Level (mm)				Linear Creep[a]		Linear Stripping[b]	
				5k pass	10k pass	15k pass	20k pass	Slope	Intercept	Slope	Intercept
1	7.2	3400	4250	---[c]	---[c]	---[c]	---[c]	1746	4.1	2954	0.1
2	7.5	4800	6100	10.2	---[c]	---[c]	---[c]	1047	4.6	2212	-1.0
3	7.3	2350	2900	---[c]	---[c]	---[c]	---[c]	2308	5.5	2836	4.2
4	7.7	3100	4100	13.6	---[c]	---[c]	---[c]	1590	5.1	2588	1.9

a) Slope (10^{-6} pass per 1-mm rut) and intercept (mm) parameters for fit of line to the linear creep region.

b) Slope (10^{-6} pass per 1-mm rut) and intercept (mm) parameters for fit of line to the linear stripping region.

c) Specimens reached termination rut depth before reaching this pass level.

Table A19. Hamburg data for all PPLC mixtures produced with reheating.

Mix ID	V_a (%)	SIP	$P_{12.5}$	Rut Depth by Pass Level (mm)				Linear Creep[a]		Linear Stripping[b]	
				5k pass	10k pass	15k pass	20k pass	Slope	Intercept	Slope	Intercept
1	7.4	10500	17150	5.6	7.7	10.2	---[c]	402	3.6	583	1.8
2	7.5	8950	11000	7.2	8.8	---[c]	---[c]	609	4.1	1543	-4.0
3	7.1	5950	7600	10.0	---[c]	---[c]	---[c]	1091	4.3	1542	2.0
4	7.1	8550	10450	7.6	10.8	---[c]	---[c]	672	4.2	1503	-2.3

a) Slope (10^{-6} pass per 1-mm rut) and intercept (mm) parameters for fit of line to the linear creep region.

b) Slope (10^{-6} pass per 1-mm rut) and intercept (mm) parameters for fit of line to the linear stripping region.

c) Specimens reached termination rut depth before reaching this pass level.

Table A20. Hamburg data for all PPFC mixtures.

Mix ID	V_a (%)	SIP	$P_{12.5}$	Rut Depth by Pass Level (mm)				Linear Creep[a]		Linear Stripping[b]	
				5k pass	10k pass	15k pass	20k pass	Slope	Intercept	Slope	Intercept
1	4.4	---[d]	140	---[c]	---[c]	---[c]	---[c]	3177	8.0	---[d]	---[d]
2	5.2	---[d]	1200	---[c]	---[c]	---[c]	---[c]	3505	8.3	---[d]	---[d]
3	4.9	---[d]	1750	---[c]	---[c]	---[c]	---[c]	2977	7.2	---[d]	---[d]
4	5.8	---[d]	700	---[c]	---[c]	---[c]	---[c]	10574	6.9	---[d]	---[d]

a) Slope (10^{-6} pass per 1-mm rut) and intercept (mm) parameters for fit of line to the linear creep region.

b) Slope (10^{-6} pass per 1-mm rut) and intercept (mm) parameters for fit of line to the linear stripping region.

c) Specimens reached termination rut depth before reaching this pass level.

d) Specimens had early rutting failure and did not exhibit SIPs.

Table A21. APA data for LC-1 testing of PPLC mixture.

Preparation Method	Load Condition	Test Temp (°C)	Mix ID	V_a (%)	Cycles to R_D = 10 mm	R_D at 4k Cycles	a^a	b^a	R^{2a}
PPLC no reheat	LC-1	64	1	3.4	3347	---[b]	0.1377	0.5274	0.99
				5.8	1102	---[b]	0.1893	0.5647	0.99
			2	3.3	7554	6.2	0.1633	0.4463	0.95
				6.1	1520	---[b]	0.0729	0.6711	0.99
			3	3.2	3343	11.6	0.0593	0.6268	0.98
				6.1	1093	---[b]	0.1112	0.6404	0.99
			4	3.8	2280	---[b]	0.0919	0.6011	0.99
				6.2	1749	---[b]	0.1490	0.5597	0.99
PPLC reheat	LC-1	64	1	3.3	19750 est.[c]	4.3	0.0621	0.5132	0.99
				6.6	5032	9.0	0.1057	0.5332	0.99
			2	3.4	38500 est.[c]	3.4	0.0811	0.4555	0.99
				6.6	2999	---[b]	0.0681	0.6226	0.99
			3	2.0	17750 est.[c]	4.9	0.1045	0.4660	0.99
				6.1	2721	---[b]	0.1130	0.5445	0.99
			4	2.8	7808	6.0	0.0974	0.5030	0.98
				6.5	2003	---[b]	0.1789	0.5275	0.99

a) The regression constants *a* and *b* and the R^2 values refer to Equation 1.

b) Specimen reached terminal rut depth before 4,000 cycles.

c) Estimated from Equation 1 regression since specimen did not reach 10-mm of rutting during testing,

Table A22. APA data for LC-1 testing of PPFC mixture.

Preparation Method	Time of Coring	Test Temp (°C)	Mix ID	V_a (%)	Cycles to R_D = 10 mm	R_D at 4k Cycles	a^a	b^a	R^{2a}
PPFC	< 1 week after placement	64	1	5.1	150	---[b]	---[b]	---[b]	---[b]
			2	4.9	109	---[b]	---[b]	---[b]	---[b]
			3	4.6	228	---[b]	---[b]	---[b]	---[b]
			4	5.7	175	---[b]	---[b]	---[b]	---[b]
	18 weeks after placement	64	1	4.6[c]	115	---[b]	---[b]	---[b]	---[b]
			2	5.0[c]	310	---[b]	---[b]	---[b]	---[b]
			3	4.7[c]	239	---[b]	---[b]	---[b]	---[b]
			4	5.7[c]	73	---[b]	---[b]	---[b]	---[b]
	32 weeks after placement	64	1	5.6	267	---[b]	---[b]	---[b]	---[b]
			2	6.1	231	---[b]	---[b]	---[b]	---[b]
			3	6.8	158	---[b]	---[b]	---[b]	---[b]
			4	6.3	287	---[b]	---[b]	---[b]	---[b]

a) The regression constants *a* and *b* and the R^2 values refer to Equation 1.

b) Specimen reached terminal rut depth before 4,000 cycles.

c) Average air voids of the test item since measured air voids were not available for the specimens

Table A23. APA data for LC-2 testing of PPLC mixture.

Preparation Method	Load Condition	Test Temp (°C)	Mix ID	V_a (%)	Cycles to R_D = 10 mm	R_D at 4k Cycles	a[a]	b[a]	R^2[a]
PPLC no reheat	LC-2	43	1	5.9	---[b]	5.8	0.1372	0.4539	0.99
			2	6.1	---[b]	3.6	0.1242	0.4060	0.99
			3	5.7	---[b]	6.5	0.1162	0.4869	0.99
			4	7.3	---[b]	6.0	0.0950	0.4999	0.99
PPLC reheat	LC-2	37	1	5.2	---[b]	2.2	0.0408	0.4810	0.99
			2	5.3	---[b]	2.7	0.0698	0.4396	0.99
			3	5.0	---[b]	3.8	0.0958	0.4435	0.99
			4	5.2	---[b]	3.7	0.1005	0.4318	0.99
	LC-2	43	1	5.0	---[b]	3.5	0.0719	0.4715	0.99
				6.5	---[b]	3.0	0.1315	0.3768	0.99
			2	5.0	---[b]	4.4	0.0967	0.4582	0.99
				6.5	---[b]	3.8	0.1366	0.4000	0.99
			3	5.0	---[b]	6.2	0.0844	0.5188	0.99
				6.0	---[b]	4.6	0.1182	0.4426	0.99
			4	4.9	---[b]	5.7	0.0866	0.5031	0.99
				6.5	---[b]	4.3	0.1392	0.4124	0.99
	LC-2	49	1	5.0	---[b]	5.6	0.1164	0.4686	0.99
			2	5.0	---[b]	6.4	0.2517	0.3912	0.99
			3	5.0	---[b]	9.0	0.2115	0.4543	0.99
			4	5.0	---[b]	8.5	0.1223	0.5101	0.99

a) The regression constants *a* and *b* and the R^2 values refer to Equation 1.

b) Specimen rutting was less than 10 mm at conclusion of test.

Table A24. APA data for LC-2 testing of PPFC mixture.

Preparation Method	Time of Coring	Test Temp (°C)	Mix ID	V_a (%)	Cycles to R_D = 10 mm	R_D at 4k Cycles	a[a]	b[a]	R^2[a]
PPFC	4 weeks after placement	43	1	4.1	895	---[b]	0.0251	0.8676	0.95
			2	4.8	825	---[b]	0.1375	0.6278	0.92
			3	3.3	708	---[b]	0.0396	0.8376	0.98
			4	5.4	347	---[b]	---	---	---
	18 weeks after placement	43	1	4.6[c]	1219	---[b]	0.0002	1.5227	0.99
			2	5.0[c]	1382	---[b]	0.0122	0.9144	0.98
			3	4.7[c]	966	---[b]	0.0419	0.7816	0.94
			4	5.7[c]	745	---[b]	0.0646	0.7602	0.96
	32 weeks after placement	37	1	3.9	4542	9.2	0.0652	0.5919	0.98
			2	5.2	4094	9.8	0.0184	0.7553	0.99
			3	3.5	2899	10.9	0.0604	0.6324	0.99
			4	4.8	5610	8.5	0.0909	0.5444	0.98
		43	1	3.9	3570	10.7	0.0552	0.6356	0.92
			2	4.8	1507	---[b]	0.0019	1.1603	0.98
			3	3.8	2011	---[b]	0.0365	0.7310	0.98
			4	5.2	1590	---[b]	0.1741	0.5460	0.99
		49	1	4.4	1048	---[b]	0.1069	0.6485	0.99
			2	4.9	968	---[b]	0.1514	0.6057	0.99
			3	4.7	667	---[b]	0.3809	0.4997	0.99
			4	5.2	654	---[b]	0.5668	0.4413	0.99

a) The regression constants *a* and *b* and the R^2 values refer to Equation 1.

b) Specimen reached terminal rut depth before 4,000 cycles.

c) Average air voids of the test item since measured air voids were not available for the specimens.

Table A25. |*E**| data for plant-produced mixture 1.

Test Temperature	Test Frequency	Replicate 1		Replicate 2		Replicate 3		Average	
		|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*
(°C)	(Hz)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)
21	25	1952	9.8	2302	6.69	1595	11.7	1950	9
	10	1777	11.5	2108	13.58	1605	13.3	1830	13
	5	1632	13.1	1874	14.4	1468	14.5	1658	14
	1	1232	17.5	1386	15.0	1236	16.7	1285	16
	0.5	1036	17.9	1285	15.0	1130	19.6	1150	17
	0.1	758	21.6	799	23.2	641	25.6	733	23
37	25	1631	12.6	1724	19.8	1191	19.9	1515	17
	10	1184	15.8	1243	17.8	1011	18.1	1146	17
	5	1066	15.8	1057	23.0	955	19.5	1026	19
	1	726	19.1	741	19.0	648	20.9	705	20
	0.5	594	19.4	619	21.8	565	18.7	593	20
	0.1	366	23.7	374	23.7	338	24.5	359	24
54	25	728	12.8	752	13.1	672	12.9	717	13
	10	595	21.0	589	17.3	613	17.1	599	18
	5	489	17.3	487	16.2	482	17.9	486	17
	1	357	14.4	368	158.5	345	163.1	357	14
	0.5	271	82.4	174	74.9	155	120.2	200	16
	0.1	200	20.9	211	19.3	208	20.9	206	20
Specimen Air Voids (%)		2.4		2.4		2.6		2.5	

Table A26. |*E**| data for plant-produced mixture 2.

Test Temperature	Test Frequency	Replicate 1		Replicate 2		Replicate 3		Average	
		|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*
(°C)	(Hz)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)
21	25	1849	9.2	2093	3.36	2039	11.5	1994	8
	10	1776	7.9	1852	7.35	1919	12.5	1849	9
	5	1767	9.5	1726	16.4	1758	9.5	1750	12
	1	1445	14.5	1353	18.3	1403	15.8	1400	16
	0.5	1262	16.2	1212	17.1	1104	22.1	1193	18
	0.1	816	19.0	736	24.7	789	24.3	780	23
37	25	1510	12.8	1555	14.5	1475	18.1	1513	15
	10	1273	18.5	1195	18.0	1203	17.8	1224	18
	5	1074	18.2	1082	21.6	1026	19.6	1061	20
	1	717	22.7	746	23.3	713	21.6	725	23
	0.5	546	23.8	569	14.5	630	16.4	582	18
	0.1	390	24.4	362	22.6	376	26.2	376	24
54	25	663	15.9	815	10.7	793	19.0	757	15
	10	625	14.9	606	17.4	583	16.0	605	16
	5	554	14.9	518	15.9	532	13.8	535	15
	1	390	159.4	376	13.3	406	74.9	391	14
	0.5	197	94.1	116	138.5	126	43.4	146	18
	0.1	226	21.7	211	21.6	223	22.7	220	22
Specimen Air Voids (%)		3.2		3.2		2.9		3.1	

Table A27. |*E**| data for plant-produced mixture 3.

Test Temperature	Test Frequency	Replicate 1		Replicate 2		Replicate 3		Average	
		|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*
(°C)	(Hz)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)
21	25	2048	10.4	2046	1.9	1918	12.8	2004	8
	10	1883	6.9	1960	12.84	1813	13.1	1885	11
	5	1867	9.6	2130	11.5	1646	14.2	1881	12
	1	1225	15.5	1359	15.4	1242	15.4	1275	15
	0.5	1133	21.9	1136	18.9	1139	19.6	1136	20
	0.1	713	25.1	791	24.3	718	26.7	741	25
37	25	1415	18.4	1497	22.6	1268	18.1	1393	20
	10	1168	16.6	1257	20.7	1071	17.0	1165	18
	5	1155	20.6	1013	20.7	935	18.3	1034	20
	1	652	19.2	628	22.3	636	22.6	639	21
	0.5	560	21.8	512	21.4	525	18.2	532	20
	0.1	371	23.0	338	24.1	329	24.4	346	24
54	25	762	17.4	746	16.5	771	16.0	760	17
	10	578	17.7	585	15.8	578	15.9	580	16
	5	537	16.9	446	15.9	487	15.7	490	16
	1	382	12.4	380	11.1	374	11.9	379	12
	0.5	115	47.5	76	146.5	136	47.3	109	18
	0.1	209	21.9	194	20.0	203	20.7	202	21
Specimen Air Voids (%)		1.4		1.7		1.5		1.5	

Table A28. |*E**| data for plant-produced mixture 4.

Test Temperature	Test Frequency	Replicate 1		Replicate 2		Replicate 3		Average	
		|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*	|*E**|	*θ*
(°C)	(Hz)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)	(MPa)	(deg)
21	25	2418	3.0	1947	14.84	2284	11.6	2216	10
	10	2693	11.5	1847	9.52	2021	8.4	2187	10
	5	2265	17.7	1895	12.2	1812	14.0	1991	15
	1	1705	23.1	1415	15.4	1465	21.2	1528	20
	0.5	1310	23.5	1154	18.8	1108	15.6	1191	19
	0.1	853	34.2	808	21.2	832	25.1	831	27
37	25	1516	18.2	1708	17.4	1658	19.0	1627	18
	10	1361	22.7	1280	20.4	1372	16.0	1338	20
	5	1087	19.3	1202	19.5	1115	22.3	1135	20
	1	795	21.9	798	18.6	747	22.6	780	21
	0.5	615	19.6	668	16.5	544	20.5	609	19
	0.1	403	24.0	410	23.7	375	24.1	396	24
54	25	1005	10.1	862	20.4	690	20.6	852	17
	10	637	17.3	627	19.9	713	18.5	659	19
	5	552	15.8	545	21.4	537	17.5	545	18
	1	432	72.6	440	16.7	417	10.1	430	16
	0.5	125	6.0	310	43.8	437	72.1	291	14
	0.1	217	21.7	231	21.6	211	22.1	220	22
Specimen Air Voids (%)		1.8		1.5		1.8		1.7	

Figure A5. |*E**| master curve for plant-produced mixture 1.

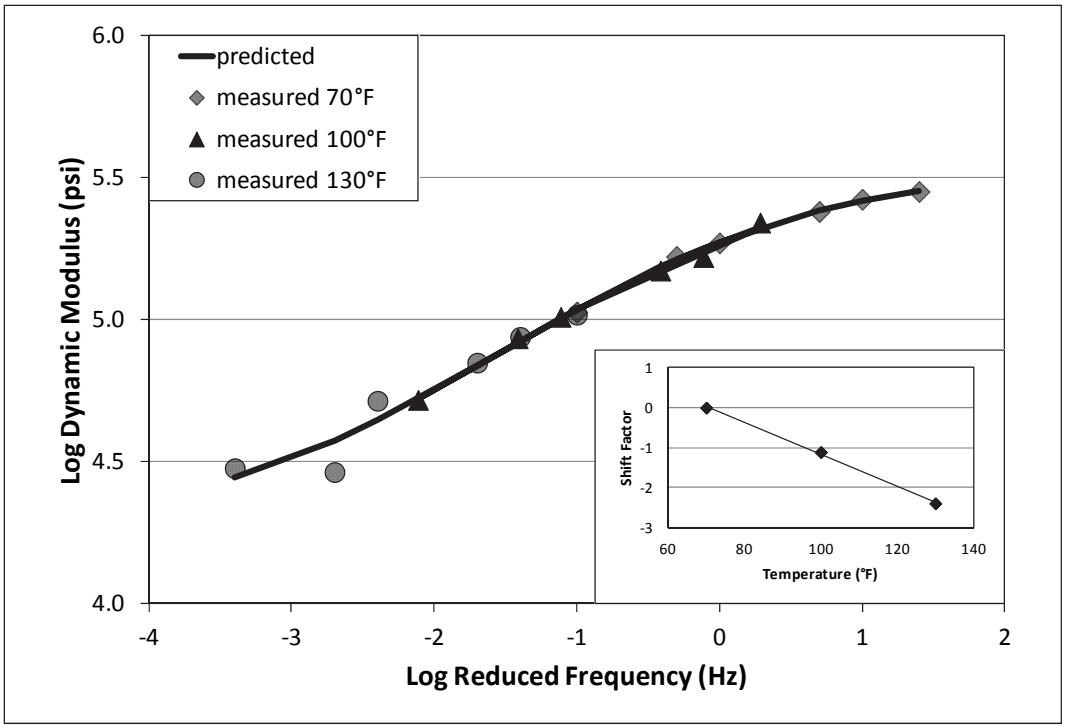


Figure A6. |*E**| master curve for plant-produced mixture 2.

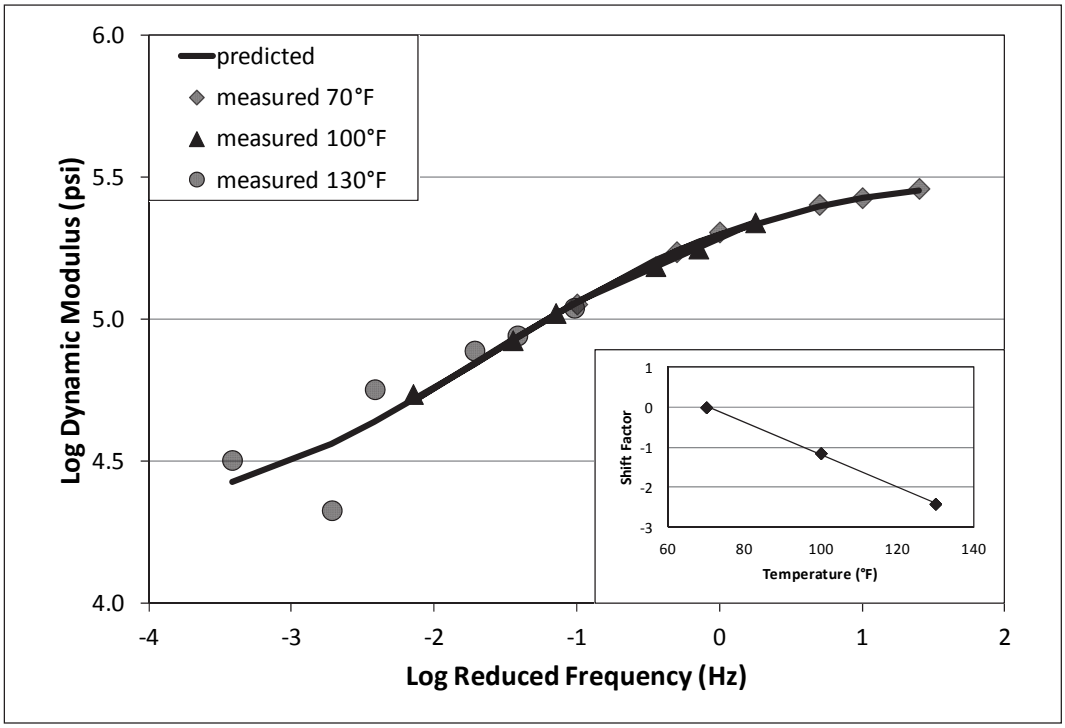


Figure A7. |*E**| master curve for plant-produced mixture 3.

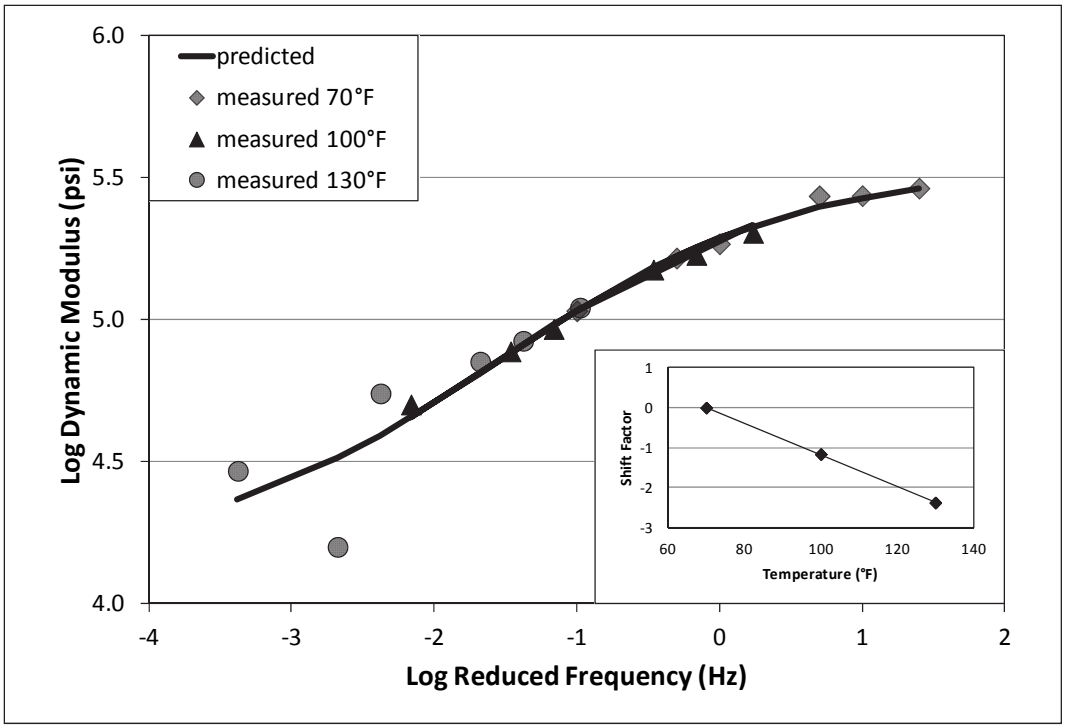
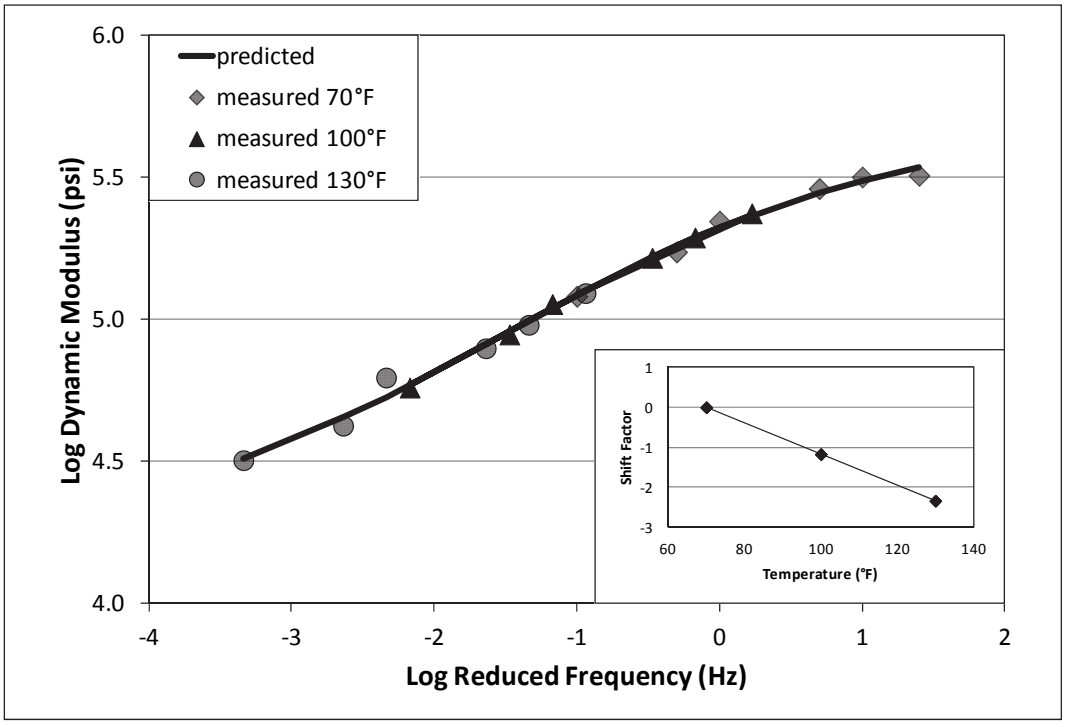


Figure A8. |*E**| master curve for plant-produced mixture 4.



REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
December 2013	Final	

4. TITLE AND SUBTITLE

Laboratory Performance Testing of Warm-Mix Asphalt Technologies for Airfield Pavements

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Geotechnical and Structures Laboratory
US Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/GSL TR-13-41

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

US Air Force Civil Engineering Center
139 Barnes Drive, Suite 1
Tyndall AFB, FL 32403-5319

10. SPONSOR/MONITOR'S ACRONYM(S)

AFCEC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report presents results from testing warm-mix asphalt (WMA) mixtures designed for airfield pavements. The study was conducted in two phases. The first phase included laboratory tests on 11 WMA technologies. The tests in Phase 2 were performed on three WMA mixtures and one hot-mix asphalt (HMA) mixture produced in an asphalt plant. The evaluation included performance tests to assess WMA susceptibility to permanent deformation and moisture damage compared to HMA produced using the same aggregate blend. Although WMA exhibited poorer performance than HMA in moisture damage tests on laboratory-produced specimens, the plant-produced mix indicated very little difference compared to HMA. Rutting potential for WMA was initially somewhat greater than for HMA for mixtures produced both in the laboratory and in an asphalt plant. Differences in performance among WMA mixtures were not attributed to a specific WMA technology category. Variations in performance test results between laboratory-produced specimens and plant-produced specimens were noted, indicating a need to require performance testing as part of a comprehensive quality assurance plan. Based on the laboratory performance test results of this study, WMA is a viable alternative to HMA for wearing surfaces on airfields.

15. SUBJECT TERMS

Warm mix asphalt
Airfield
Asphalt pavement
Rutting
Moisture damage

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Jesse Doyle
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified		92	601-634-2814